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(NASA-CR-160378) SOLAR POWER SATELLITE SYSTEM DEFINITION STUDY, PHASE 2. PART 1: MIDTERM BRIEFING (Boeing Aerospace Co., Seattle, Wash.) 543 p CSCL 22B

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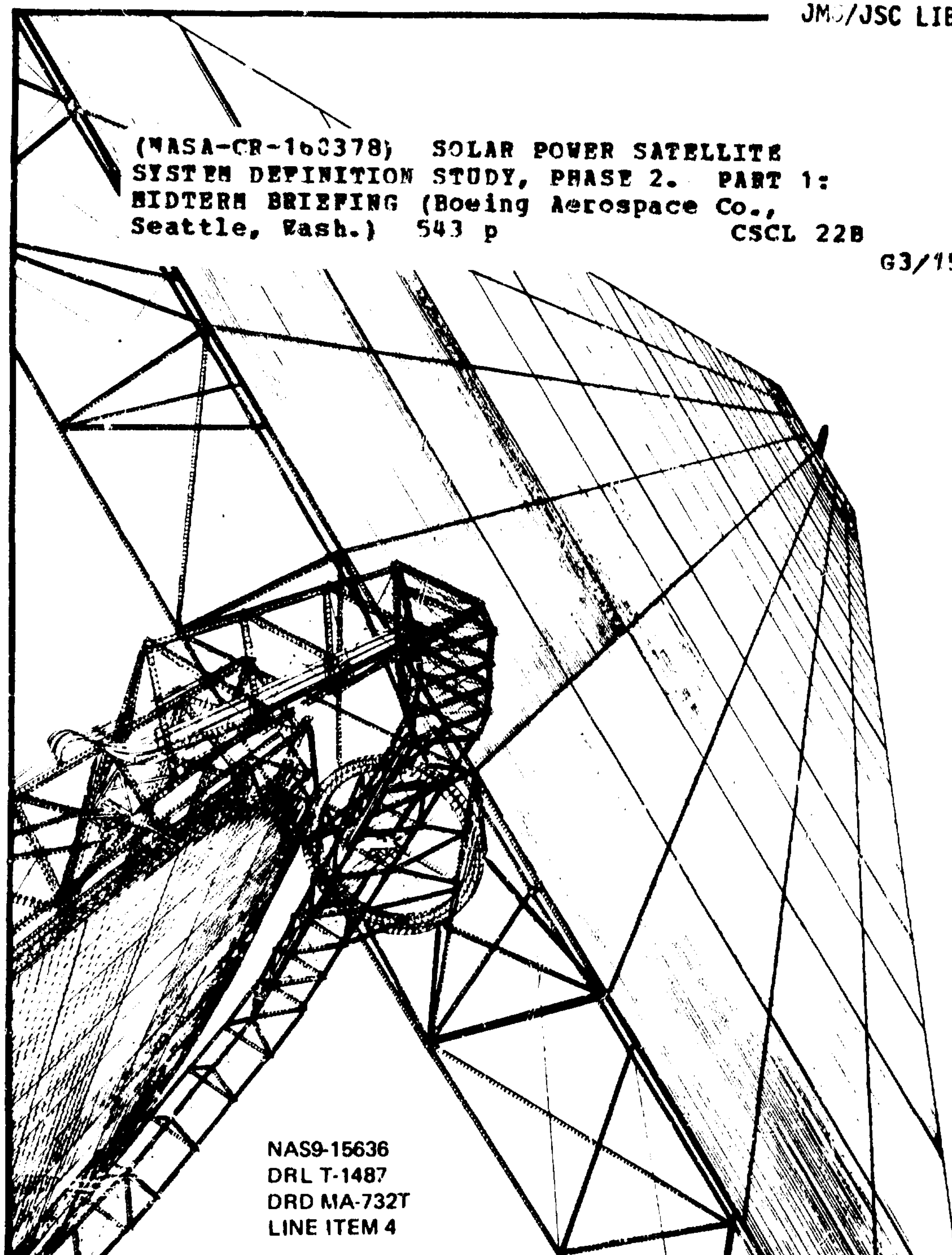
Phase 2

Midterm Briefing

D180-25402-1

NASA CR-160378



Solar Power Satellite System Definition Study

BOEING

GENERAL ELECTRIC

GRUMMAN

Arthur D Little Inc

TRW

NAS9-15636
DRL T-1487
DRD MA-732T
LINE ITEM 4

Solar Power Satellite
System Definition Study

Part I
MIDTERM BRIEFING
D180-25402-1
June 27, 1979

Approved by:
G. R. Woodcock
Study Manager

Boeing Aerospace Company
Ballistic Missiles and Space Division
P.O. Box 3999
Seattle, Washington 98124

AGENDA

The mid term briefing was conducted with the agenda shown on the facing page. Four subcontractors are working with us on this study. Of these only Grumman prepared a report for the midterm. General Electric will present their briefing in August. Arthur D. Little is required to present only at the final briefing and TRW's mission control integration task did not begin until the midterm briefing. TRW was present at the midterm to participate in splinter meetings on operations and mission control.

Agenda

EXECUTIVE SUMMARY	– G. WOODCOCK	:45
MICROWAVE POWER TRANSMISSION AND SOLID STATE	– E. NALOS	1:00
OPERATIONS ANALYSIS	– K. MILLER	1:15
CONSTRUCTION BASE	– R. McCAFFREY (GRUMMAN)	1:00
RESEARCH AND PROGRAM PLANNING	– G. WOODCOCK	1:00

EXECUTIVE SUMMARY TOPICS

The executive summary covers the subjects indicated.

SPS

Executive Summary Topics

- REFERENCE SYSTEM REVIEW
- MPTS/SOLID STATE
- OPERATIONS ANALYSIS
- RESEARCH PLANNING AND PROGRAM PLANNING
- PLANS FOR BALANCE OF STUDY

CURRENT SOLAR POWER SATELLITE PROGRAM WORK BREAKDOWN STRUCTURE

The current SPS work breakdown structure is shown in the facing tabulation.

Current Solar Power Satellite Program WBS

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SPS-2524

- 1.0 SOLAR POWER SATELLITE PROGRAM
  - 1.1 SATELLITE
    - 1.1.1 ENERGY CONVERSION
      - .1 STRUCTURE
      - .2 CONCENTRATORS
      - .3 SOLAR BLANKET
      - .4 POWER DISTR.
      - .5 THERMAL CONTROL
      - .6 MAINTENANCE
    - 1.1.2 POWER TRANSMISSION
      - .1 STRUCTURE
      - .2 TRANSMITTER SUBARRAYS
      - .3 POWER DISTR.
      - .4 THERMAL CONTROL
      - .5 CONTROL
      - .6 MAINTENANCE
      - .7 MECHANICAL POINTING [1]
    - 1.1.3 INFORMATION MANAGEMENT AND CONTROL
    - 1.1.4 ATTITUDE CONTROL AND STATIONKEEPING
    - 1.1.5 COMMUNICATIONS
    - 1.1.6 INTERFACE (ENERGY CONV./POWER TRANSMISSIONS)
    - 1.1.7 SYSTEMS TEST
  - 1.2 SPACE CONSTRUCTION AND SUPPORT
    - 1.2.1 CONSTRUCTION FACILITIES
      - .1 WORK SUPPORT
      - .2 CREW SUPPORT
      - .3 OPERATIONS
    - 1.2.2 LOGISTICS SUPPORT FACILITIES [2]
      - .1 WORK SUPPORT
      - .2 CREW SUPPORT
      - .3 OPERATIONS
    - 1.2.3 O&M SUPPORT FACILITIES
      - .1 WORK SUPPORT
      - .2 CREW SUPPORT
      - .3 OPERATIONS
  - 1.3 TRANSPORTATION
    - 1.3.1 HLLV
    - 1.3.2 COTV
    - 1.3.3 PLV
    - 1.3.4 POTV
    - 1.3.5 PM
    - 1.3.6 IOTV
    - 1.3.7 GROUND SUPPORT FACILITIES
  - 1.4 GROUND RECEIVING STATION
    - 1.4.1 SITE AND FACILITIES
    - 1.4.2 RECTENNA SUPPORT STRUCTURE
    - 1.4.3 POWER COLLECTION
    - 1.4.4 CONTROL
    - 1.4.5 GRID INTERFACE
    - 1.4.6 OPERATIONS
  - 1.5 MANAGEMENT AND INTEGRATION
    - 1.5.1 PROGRAM MANAGEMENT
    - 1.5.2 PROGRAM PLANNING AND CONTROL
    - 1.5.3 CONTRACTS ADMINISTRATION
    - 1.5.4 ENGINEERING MANAGEMENT
    - 1.5.5 MFG. MANAGEMENT
    - 1.5.6 SUPPORT MANAGEMENT
    - 1.5.7 QUALITY ASSURANCE MANAGEMENT
    - 1.5.8 CONFIGURATION MANAGEMENT
    - 1.5.9 DATA MANAGEMENT
    - 1.5.10 SYSTEMS ENGINEERING AND INTEGRATION

[2] BECOMES GEO BASE FOR THE LEO CONSTRUCTION OPTION

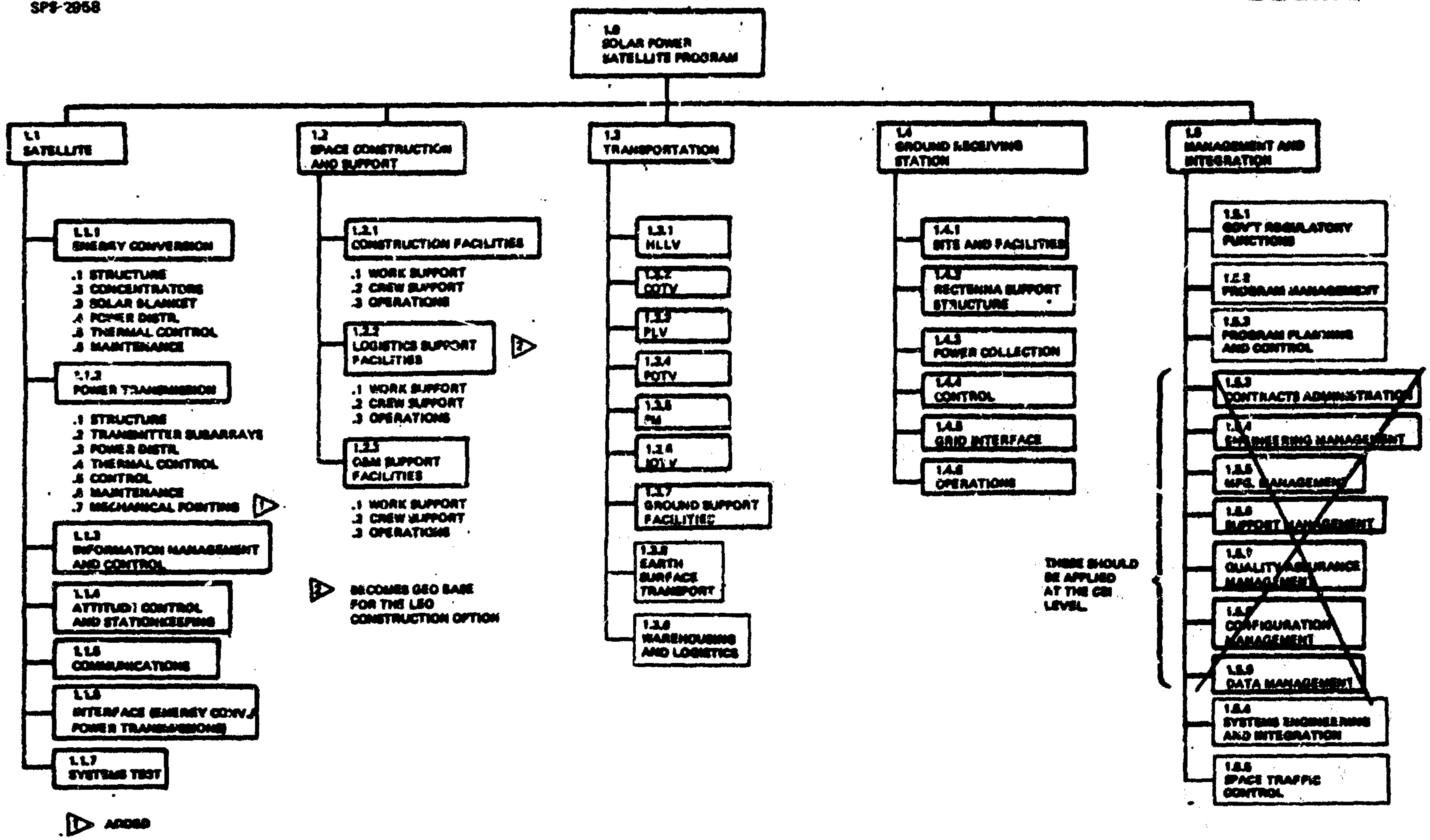
[1] ADDED

SOLAR POWER SATELLITE PROGRAM WORK BREAKDOWN STRUCTURE RECOMMENDED CHANGES

Certain changes in the WBS are recommended. Under transporation, two new items are needed: earth surface transportation and warehousing and logistics. A number of the management and integration items shown in the current work breakdown structure at the program level should be applied at the contract end item level. Further it is recommended that government regulatory functions (although presently not identified) be added, and that system engineering and integration and space traffic control be carried at the program level.

Solar Power Satellite Program WBS Recommended Changes

SPS-2958



5,000 MEGAWATT REFERENCE PHOTOVOLTAIC REFERENCE SYSTEM DESCRIPTION

This figure illustrates the system for the NASA baseline reference case of 5,000 megawatts and silicon solar blanket.

5000 Megawatt Reference Photovoltaic System Description

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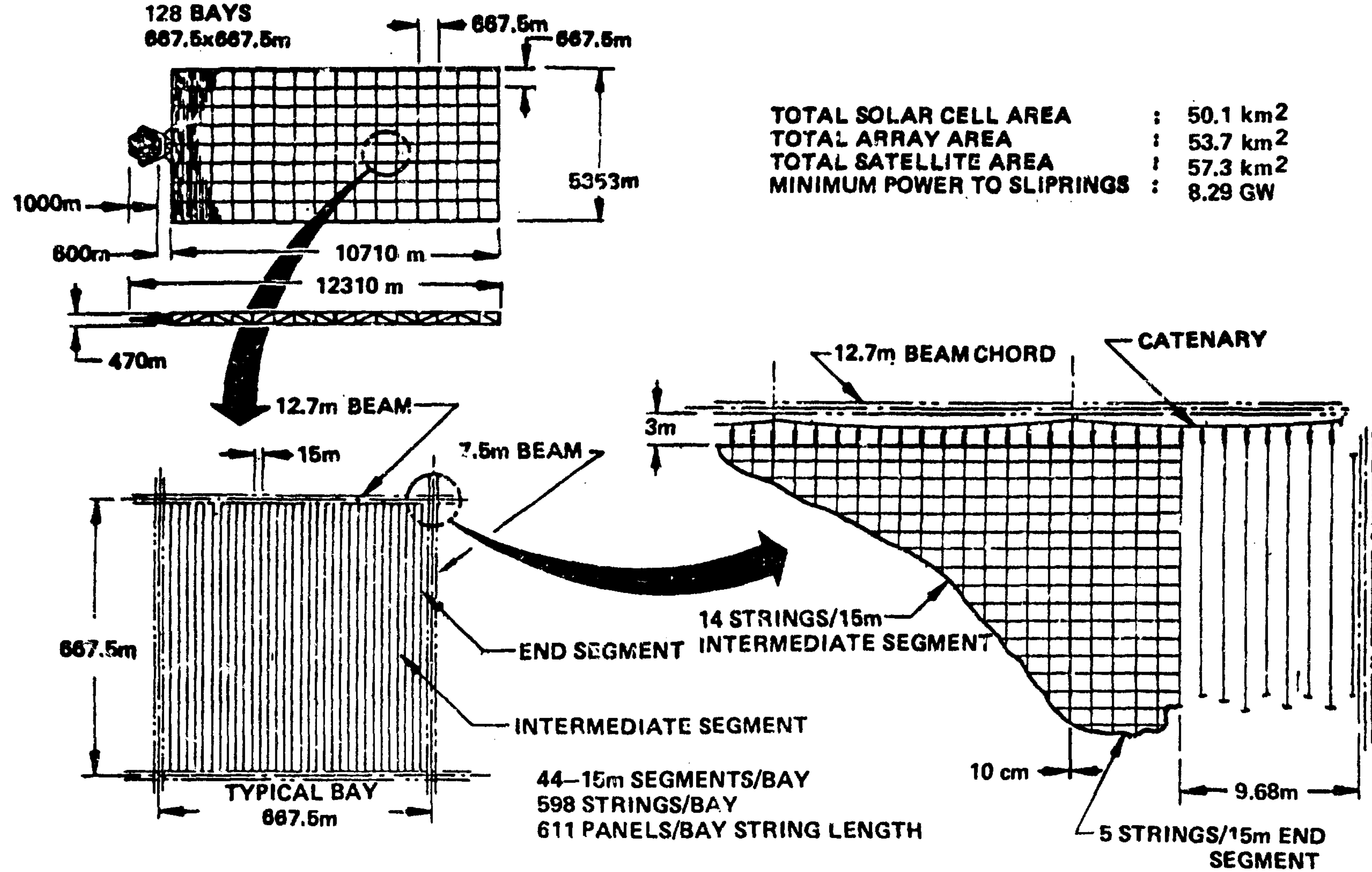
SPS-2470



REFERENCE PHOTOVOLTAIC SYSTEM DESCRIPTION

The solar blanket design has been updated to include shunting diodes required to provide shadowing protection. The shadowing protection is provided at the blanket panel level. In the event of shadowing or some other fault within the blanket, each panel can be bypassed by the shunting diodes to prevent reverse breakdown failure.

Reference Photovoltaic System Description

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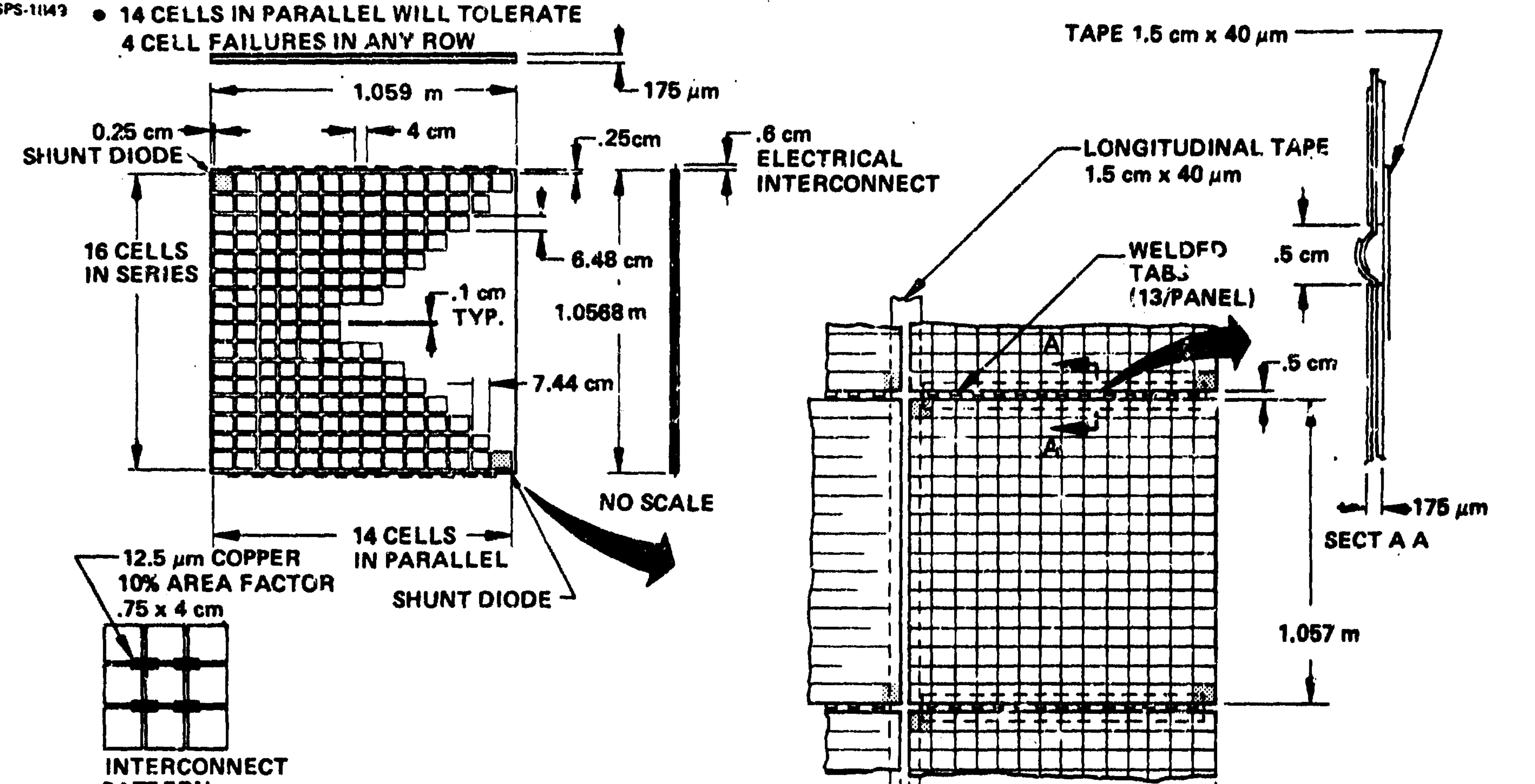
SPS-1143

- 14 CELLS IN PARALLEL WILL TOLERATE 4 CELL FAILURES IN ANY ROW



#CELLS/PANEL	:222
PANELS/BAY	:365,378
PANELS/SATELLITE	:9,353,678

SOLAR POWER SATELLITE STRUCTURAL BAY CONFIGURATION

The SPS solar array support structure is arranged in a hexahedral truss bay configuration with a total of 128 bays making up the entire structure. Each bay is 667.5 meters square. The solar array is tensioned between the type A beams in trampoline fashion. Thus, these beams are larger than the type B beams in order to carry the additional loads of solar array support tension. The structure includes an upper to lower surface cross diagonal for structural stability. Characteristics of the beams making up the structure are shown on the following page.

Solar Power Satellite Structural Bay Configuration

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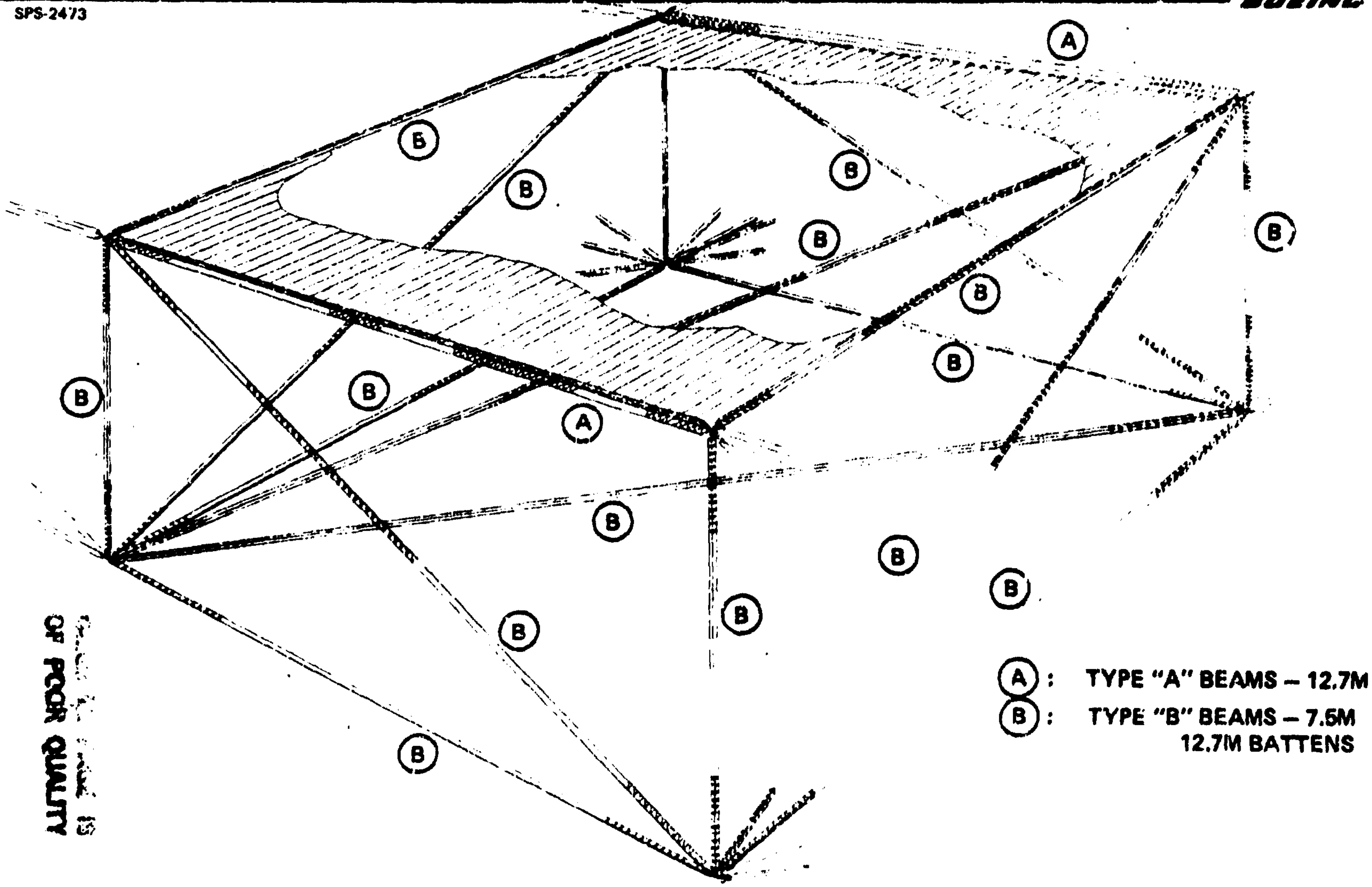
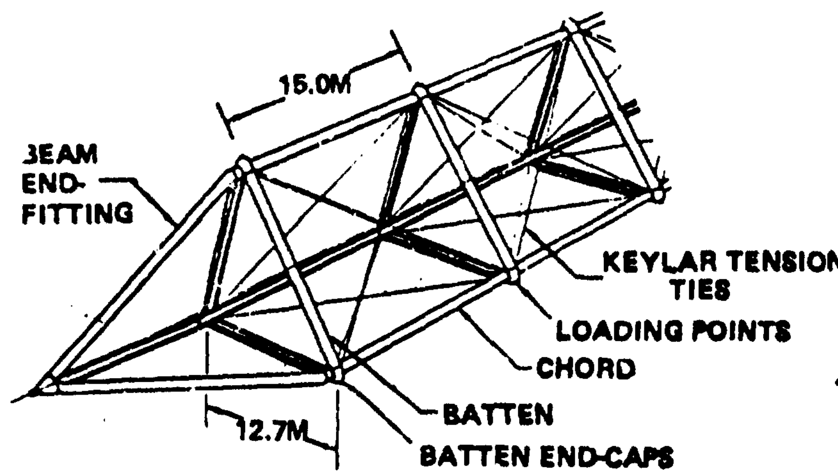
SPS-2473

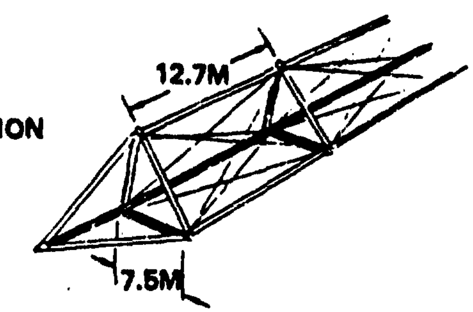


SOLAR POWER SATELLITE STRUCTURAL UPDATE BEAM CONFIGURATIONS

This chart summarizes the pertinent characteristics of the two tri-beams used in the solar array support structure.

Solar Power Satellite Structural Update Beam Configurations





ITEM	TYPE A UPPER SURFACE LONGITUDINAL BEAM	TYPE C BEAM USED IN ALL OTHER LOCATIONS
SECTION	CLOSED	OPEN
REF. SIDE LENGTH	38 CM	38CM
MAT'L THICKNESS	0.86 MM	0.71 MM
EI_X	3.39 E8 N/CM^2	1.80 E8 N/CM^2
BEAM WIDTH	12.7M	7.5M
BATTEN SPACING	15.0M	12.7M
CRITICAL LOAD	17480N (CRIP. CHORD)	7090 N(BUCK BEAM)
MASS/LENGTH	7.48 KG/M	4.11 KG/M

SOLAR CELL DEGRADATION

The expected degradation of solar cells for SPS's has been a subject of appreciable disagreement. The problems that have caused this disagreement are summarized on the facing page. The commonly used method is the so-called damage coefficient method reflected in the TRW solar cell handbook. This method has been adequate for conventional array design but recent studies have indicated that improved techniques are needed for thin solar cells and covers.

Solar Cell Degradation

- DAMAGE COEFFICIENT METHOD IS INADEQUATE* FOR THIN CELLS & COVERS
  - UNDERESTIMATES LOW ENERGY PROTON DAMAGE
  - OVERESTIMATES ELECTRON DAMAGE
  - DOES NOT CONSIDER DAMAGE GRADIENTS
- INSUFFICIENT TEST DATA EXIST FOR AN ACCURATE ASSESSMENT
- FURTHER, A RANGE OF ENVIRONMENT MODELS EXISTS

* REFERENCE: CONTRACT NAS8-30378

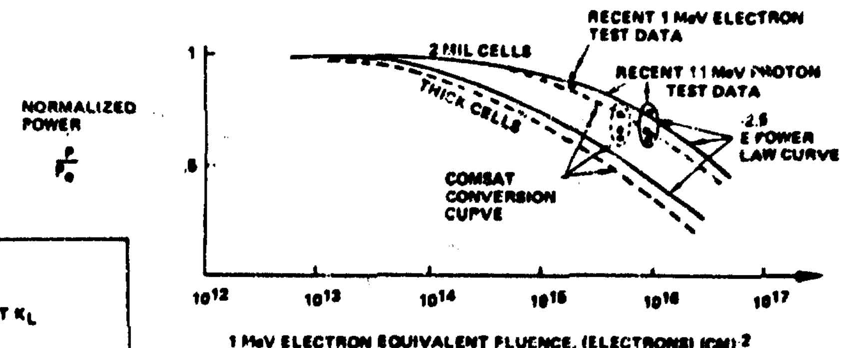
RADIATION DEGRADATION OF SILICON SOLAR CELLS

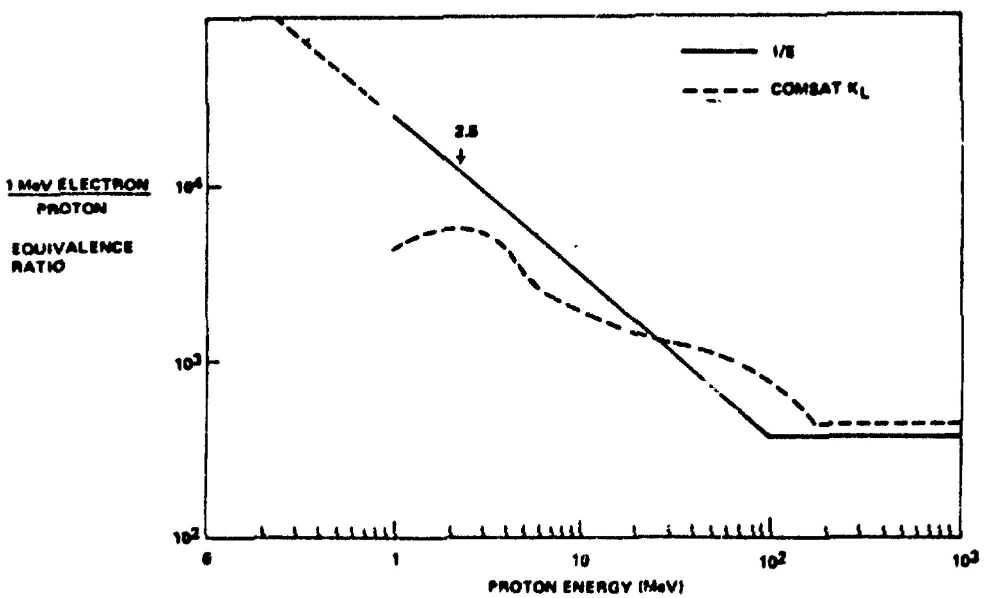
The effectiveness of protons in degrading silicon solar cells is dependent on proton energy below 100 MEV. The left-hand part of the chart shows a Comsat-derived correction factor and a power law factor derived by Wilkinson and Horne of Boeing employing the PN code. These corrections are used because damage is commonly plotted versus 1-MEV electronic equivalent fluences as shown in the upper right.

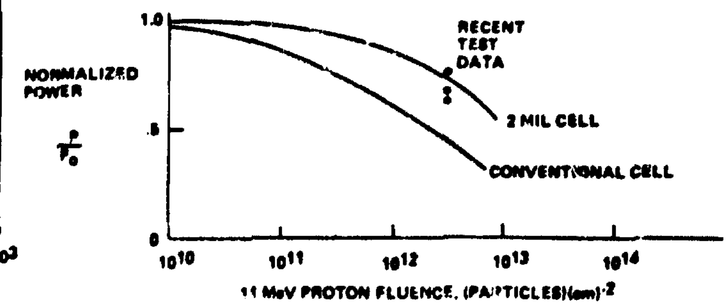
Recent Boeing test data using protons is shown in the lower right. The way these points plot on the electron equivalent fluenc curve depends on which of the extrapolations are used. It appears that the power law curve is the better extrapolation but the data scatter for existing data points is sufficiently great that firm conclusions can not be drawn.

Radiation Degradation of Si Solar Cells

SPS-2838





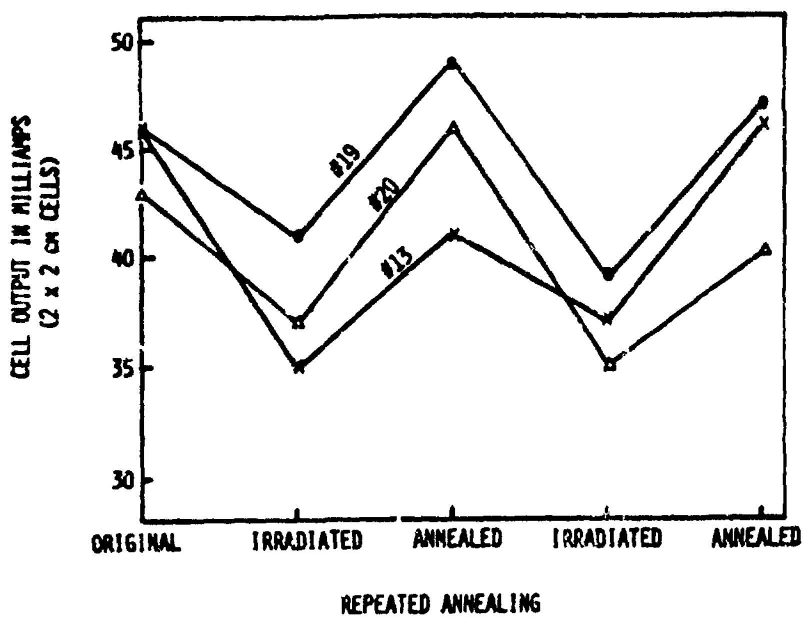


SILICON SOLAR CELL ANNEALING

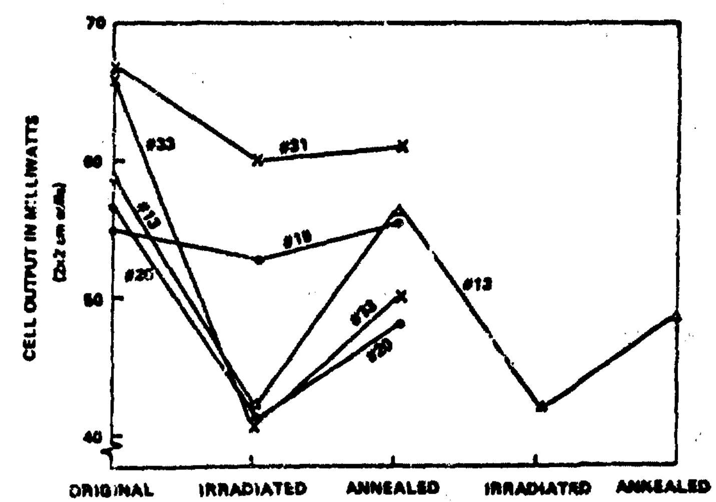
The annealing of radiation damage in silicon solar cells has been known for over 10 years. Recent experiments have concentrated on the thin solar cells currently under technology development, and on methods that may be adaptable to insitu annealing of an SPS solar array in space. Directed energy methods are attractive from this viewpoint. Illustrated on the facing page are recent results obtained with thermal bulk annealing and ovens and with directed energy laser annealing. It may be noted that the oven recovery is better than the laser recovery. This appears to be a result of the difference in time. The oven tests allowed 20 minutes for annealing whereas the laser tests allowed a few up to 10, seconds. Annealing temperatures were approximately 500°C. Attempts to anneal glass covered 50 micron solar cells were not successful because the glass coating techniques were not compatible with the annealing temperatures. Improved coating techniques are being studied under Boeing IR&D with some success, but annealing tests have not yet been conducted with these.

Silicon Solar Cell Annealing

OVEN RESULTS



LASER RESULTS



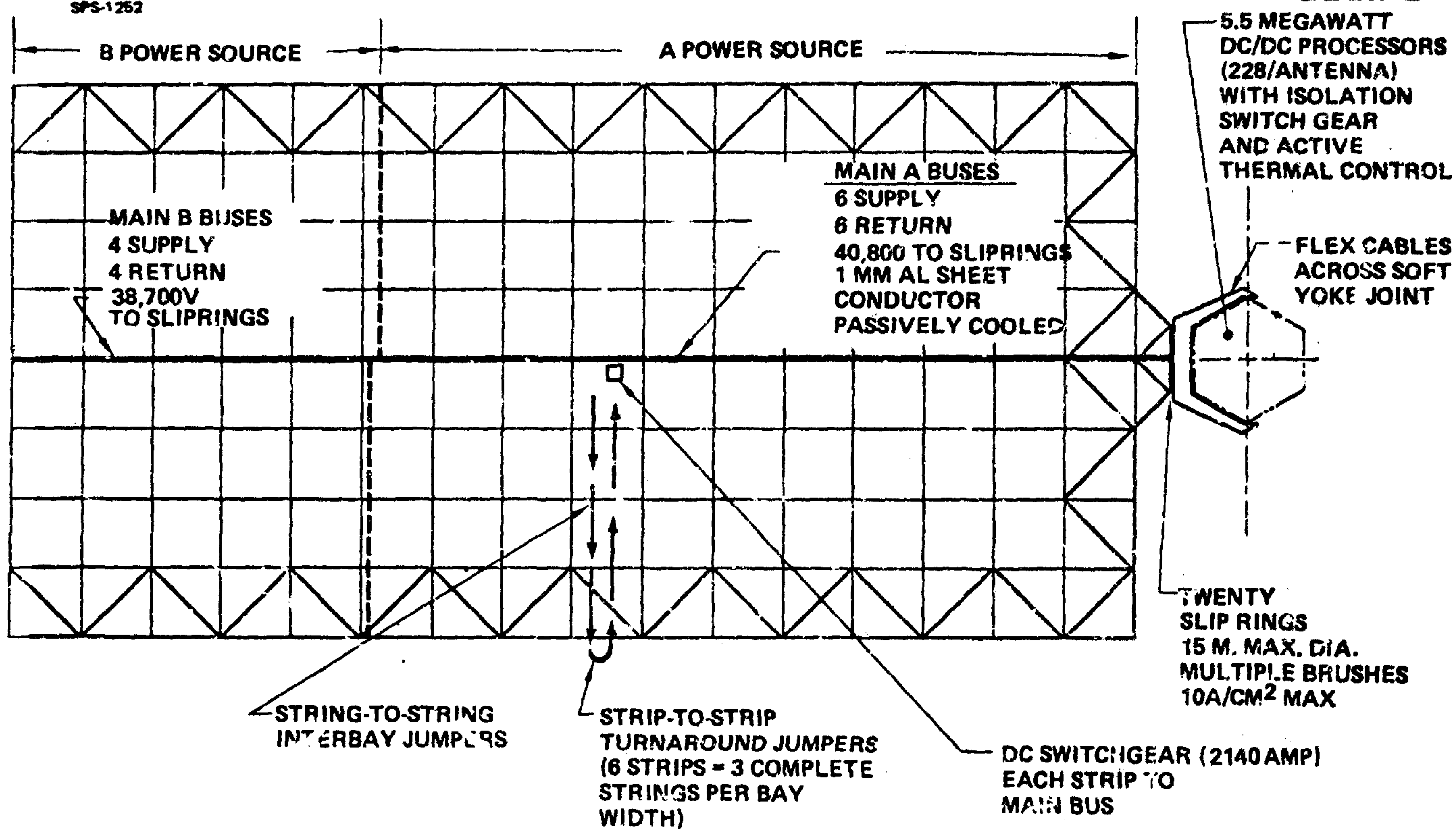
NOTE: THESE WERE ALL BARE CELLS. FURTHER DEVELOPMENT IS NEEDED IN HIGH-TEMPERATURE-COMPATIBLE GLASS ENCAPSULATION.

MULTIPLE BUS SPS POWER DISTRIBUTION

Failure effects analyses indicated that the previous three-bus configuration could cause very large fault currents in the event of certain types of arcs. Because of this problem, the bus configuration was changed to reflect the use of 10 buses independent of one another. Major characteristics of the busing system are indicated on the facing page.

Multiple Bus SPS Power Distribution

SPS-1252



SLIPRING ASSEMBLY FOR MULTIPLE BUS POWER DISTRIBUTION SYSTEM

Selection of 10 independent buses required a redesign of the slipring assembly to provide a total of 20 rings. The major features of the design are shown on the facing page.

SPS-2552

Slip Ring Assembly for Multiple Bus Power Distribution System

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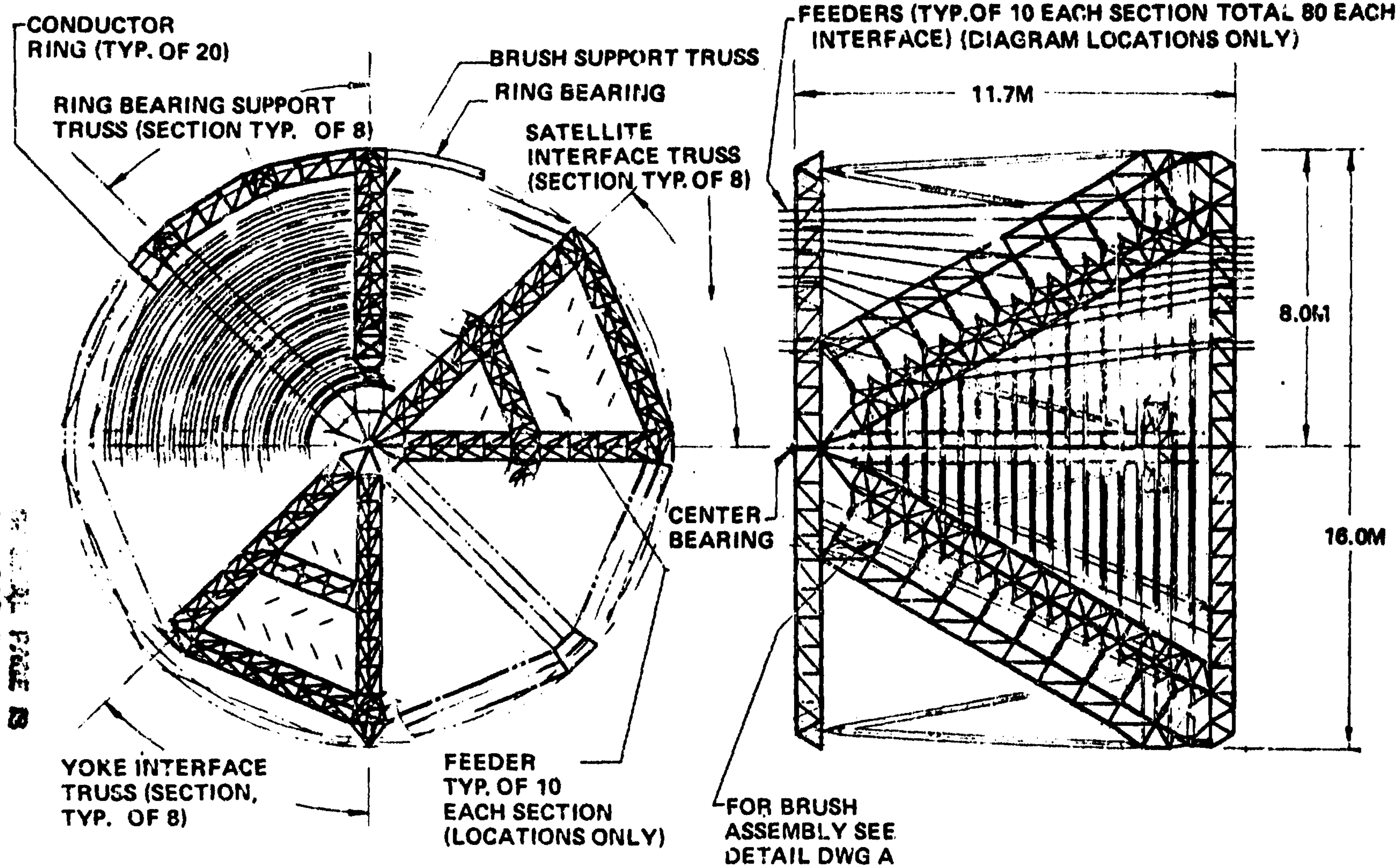
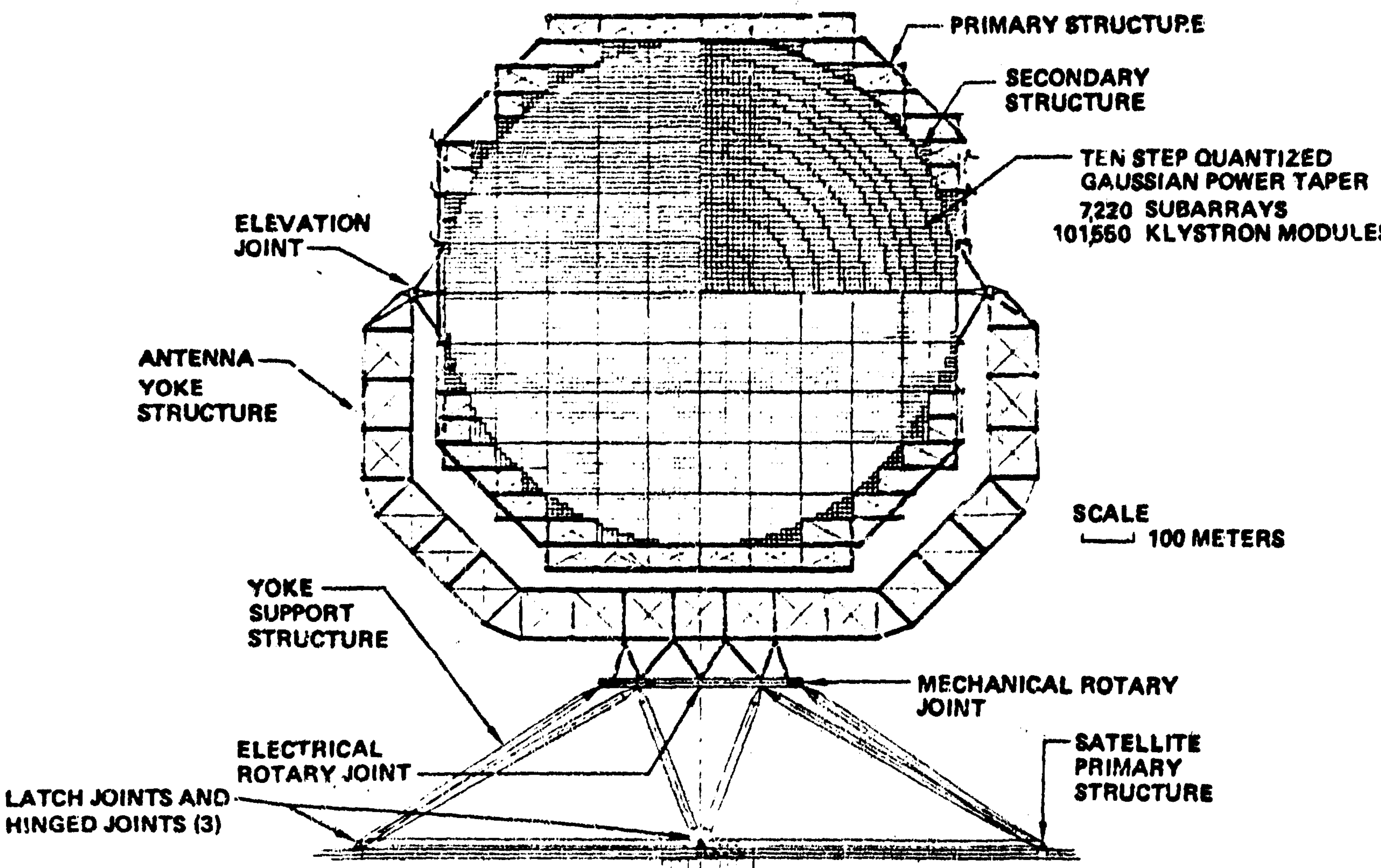


TRANSMITTER ANTENNA

The reference transmitter is a one kilometer diameter phased array operating at 2,450 megahertz. It is comprised of more than 7,000 subarrays supported by a two tier structure. The size of the subarrays has been selected to allow their transport to orbit by the heavy lift launch vehicle. Illumination of the aperture employs a 10 dB truncated gaussian taper with relative phasing across the aperture controlled by the retrodirective phase control system to focus the beam at the pilot transmitter located at the center of the receiving antenna. The antenna is supported on a yoke that turns in a rotary joint to allow the antenna to continuously face the earth ground station while the solar array continuously faces the sun. In addition, the antenna is provided with elevation drive of several degrees excursion in order to allow aiming at the appropriate earth surface latitude as determined by the location of the receiving site.

Transmitter Antenna

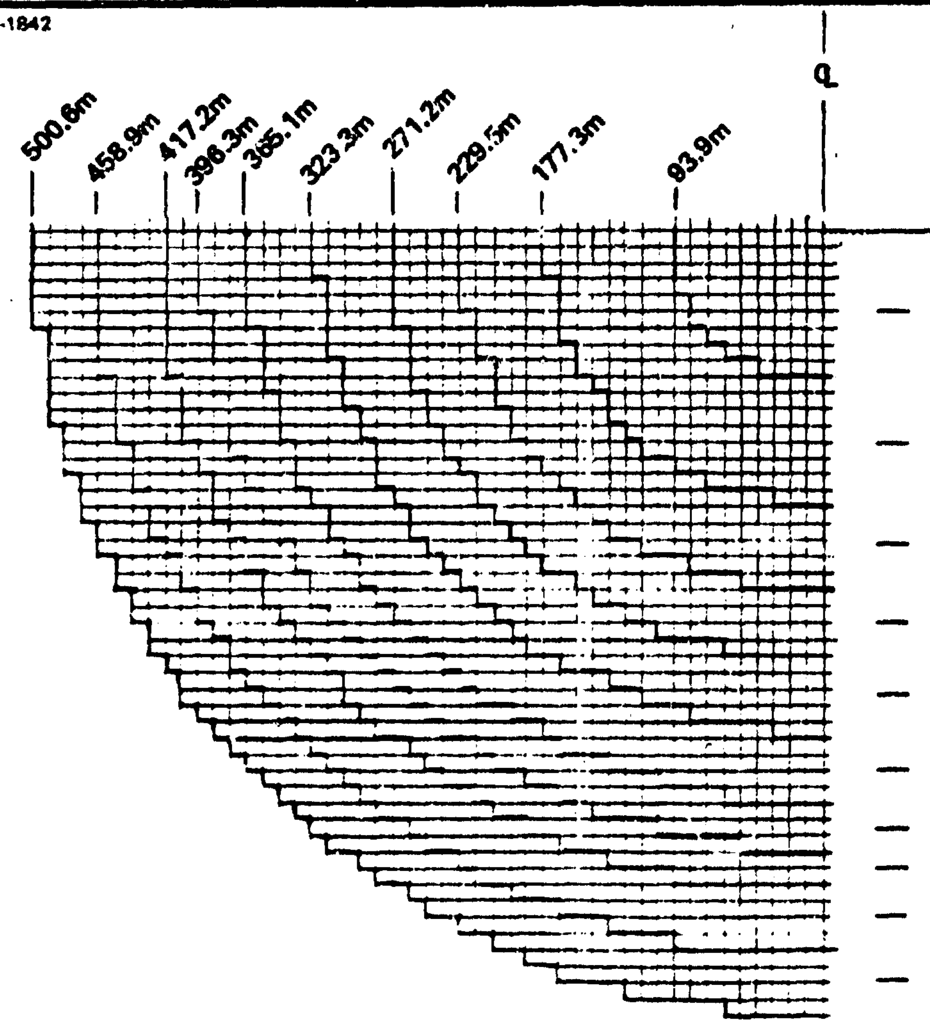


POWER TAPER INTEGRATION

The MPTS baseline uses a square subarray. The actual integration of power density rings is illustrated on this view of one-fourth of the radiating face of the antenna. The integration simulates a gaussian power taper of 9.5 dB using the quantized power levels available. Note the change in numbers of subarrays and klystron over the Part II reference system.

MPTS Reference Power Taper Integration

SPS-1842



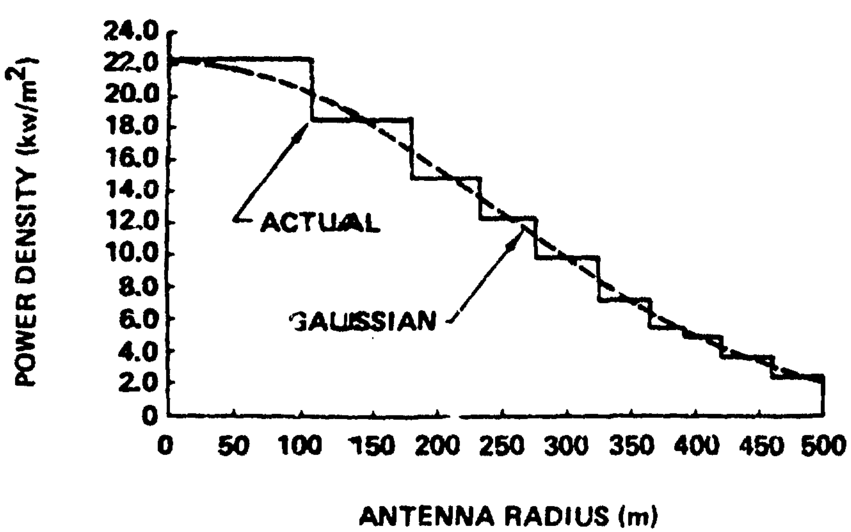
STEP	NUMBER SUBARRAYS	NUMBER KLYSTRONS/ SUBARRAYS	NUMBER KLYSTRONS
1	276	36	9,936
2	632	30	18,960
3	644	24	15,456
4	628	20	12,560
5	784	16	12,544
6	900	12	10,800
7	664	9	5,976
8	612	8	4,896
9	1,052	6	6,312
10	1,028	4	4,112
Totals	7,220		101,552

ANTENNA AND FAR FIELD GROUND DISTRIBUTION PATTERNS

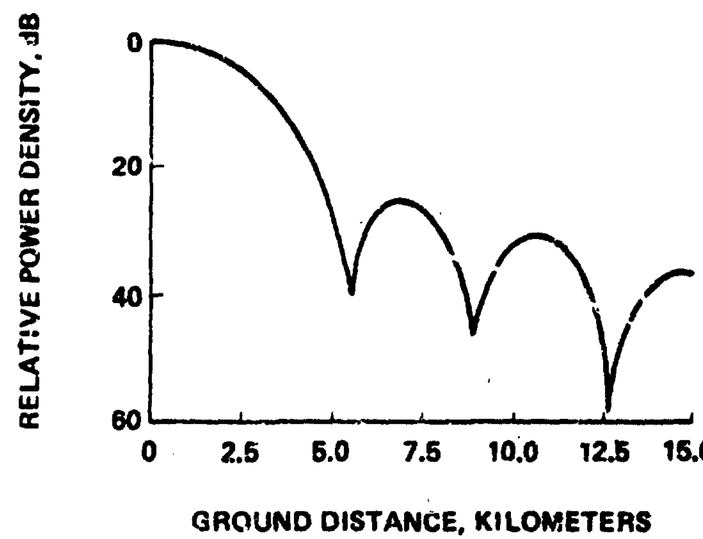
Part (A) of this figure shows the reference 10 step quantized power density shown previously. The far field ground pattern is shown in figure (B). The first side lobe peak is shown at 24.5 dB below the center-beam power density.

Taking the rectenna radius out to the first null, 6485 meters with an antenna radius of 500 meters, the beam efficiency is 94.6%.

MPTS Reference Antenna And Ground Distribution Functions



(A) ANTENNA DISTRIBUTION FUNCTION

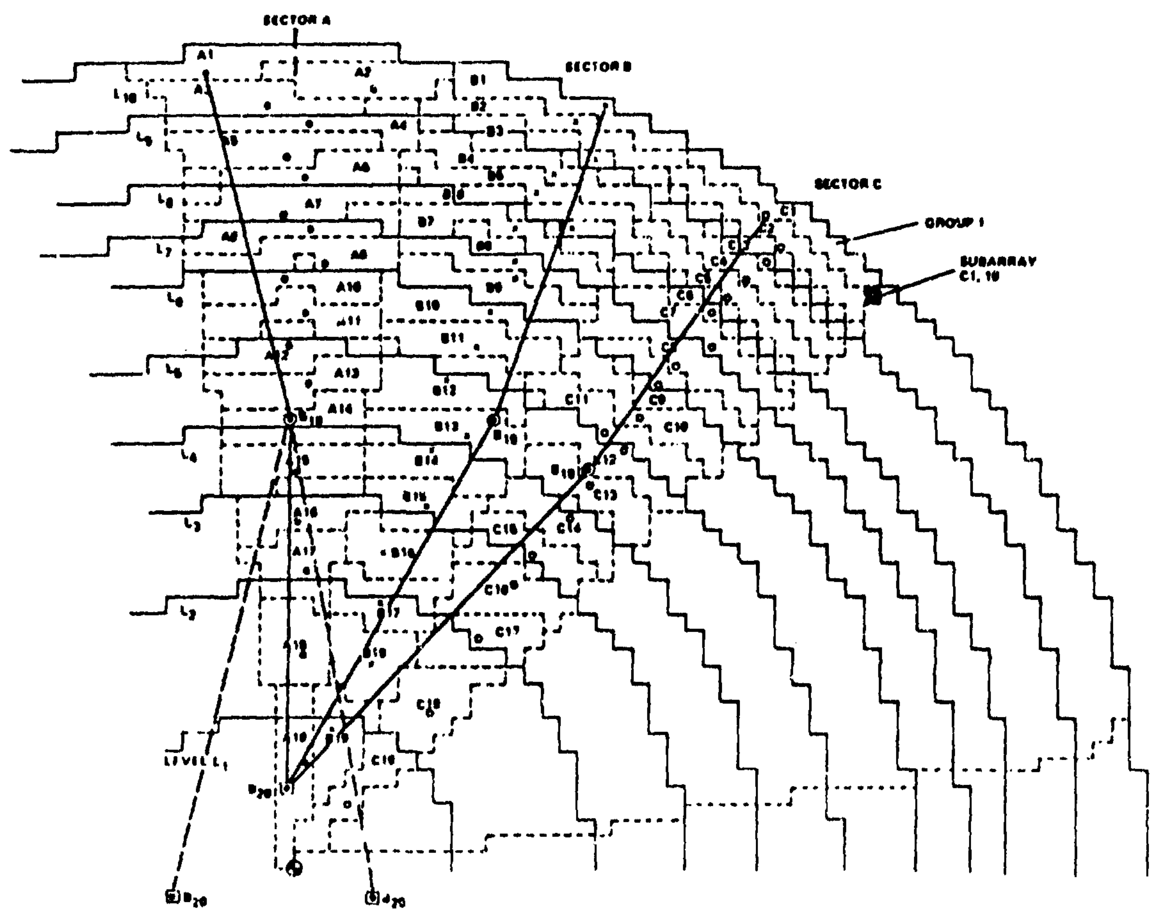


(B) FAR FIELD GROUND DISTRIBUTION

FOUR NODE PHASE DISTRIBUTION SYSTEM LAYOUT

Three sections are shown of the 4 node system selected for reliability analysis by the General Electric Co. This layout uses 20 triply redundant sections at the first level, 19 doubly redundant paths at the second level, and 19 non-redundant paths (cable and electronics) at the third level (i.e., 7220 subarrays). The fourth level provides power dividers down to the klystron module (4:1 at the center and 36:1 at the array edge), to accommodate the quantized 10 db Gaussian power taper indicated in the chart.

LOCATION OF REFERENCED PHASE REPEATER STATIONS OF SECTORS AND GROUPS



SPS MASS PROPERTIES SUMMARY

The facing page presents a tabulation of the mass properties for the current silicon reference design according to the current NASA SPS work breakdown structure.

SPS Mass Properties Summary (Values are in Metric Tons for 5-GW Silicon Baseline)

SPS-2815

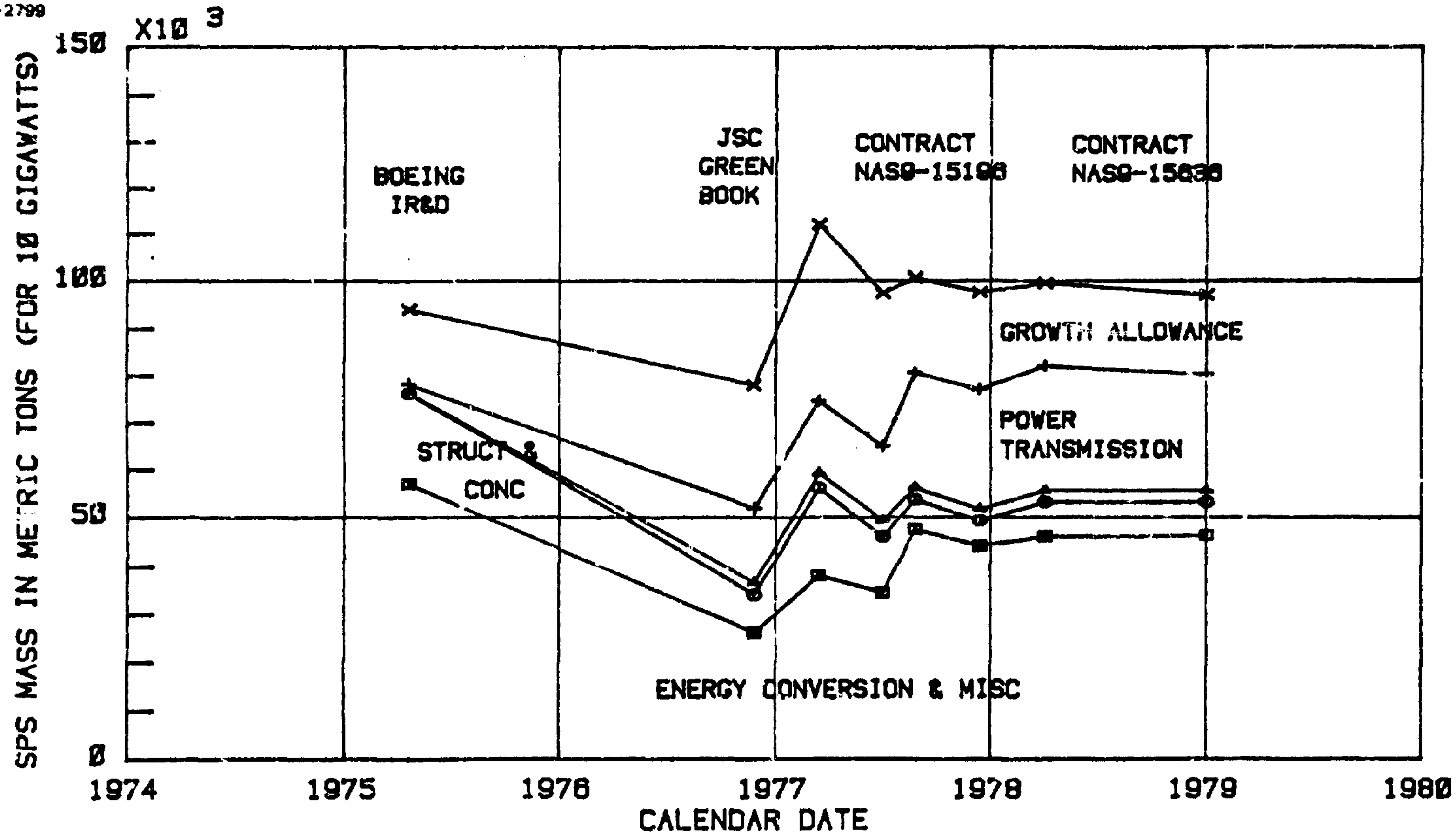
SOLAR POWER SATELLITE TOTAL	48473		
SOLAR POWER SATELLITE IDENTIFIED MASS	40060		
ENERGY CONVERSION		27235	
STRUCTURE			3383
SOLAR BLANKET			22553
POWER DISTRIBUTION & SWITCHGEAR			1213
MAINTENANCE			86
POWER TRANSMISSION		12234	
STRUCTURE			370
TRANSMITTER SUBARRAYS			9382
POWER DISTRIBUTION & CONDITIONING			2210
MAINTENANCE			144
ANTENNA MECHANICAL POINTING			128
INFORMATION MANAGEMENT & CONTROL		250	
ATTITUDE CONTROL & STATIONKEEPING		184	
COMMUNICATIONS		10	
ENERGY CONVERSION/POWER TRANSMISSION INTERFACE		147	
GROWTH & CONTINGENCY ALLOWANCE	8413		

PHOTOVOLTAIC SPS MASS HISTORY

Shown on the facing page is the history of SPS mass estimates from Boeing IR&D through the JSC Green book (the latter being an entirely independent study), and the several mass statements developed under the Boeing system definition studies for NASA/JSC. These were all photovoltaic systems, some employed concentrators and some did not.

Photovoltaic SPS Mass History

SPS-2799



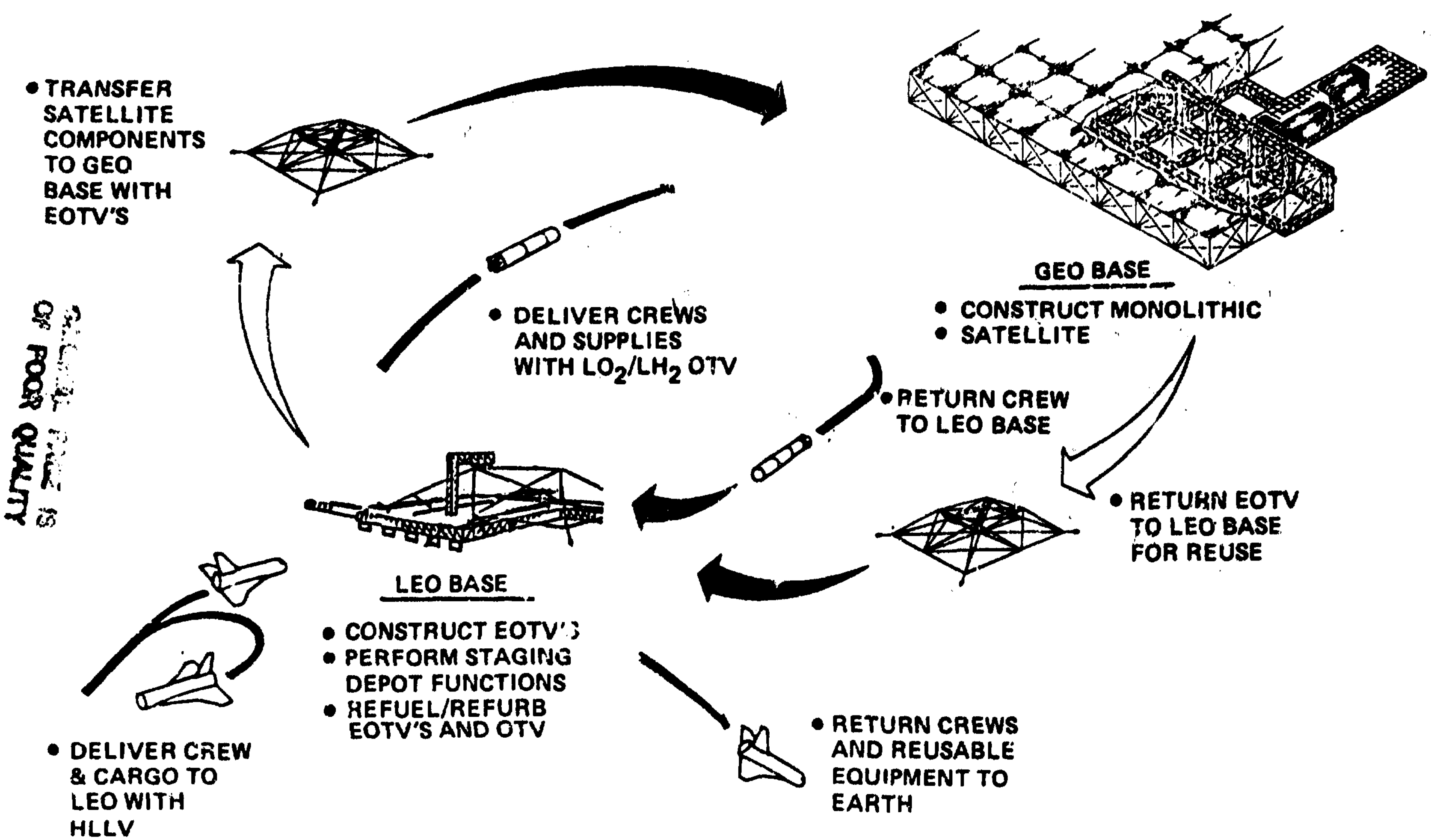
GEO CONSTRUCTION CONCEPT ELECTRIC ORBIT TRANSFER VEHICLES

The reference system employs construction of the SPS's at geosynchronous orbit. SPS hardware is prefabricated to the degree practicable on earth, shipped to low earth orbit by heavy lift launch vehicle, and transferred to a low earth orbit staging base. At this staging base, cargoes are transferred to the cargo orbit transfer vehicle which is somewhat arbitrarily sized to carry 10 HLLV payloads to geosynchronous orbit per trip. This cargo OTV is powered by a solar electric propulsion system employing argon as propellant. It returns the empty cargo containers to the staging base on its return trip. Construction and maintenance crews are delivered to low earth orbit by a modified space shuttle where they transfer to a personnel orbit transfer vehicle powered by oxygen/hydrogen rocket engines. This vehicle delivers and returns the crews to and from geosynchronous orbit where their nominal duty period is 90 days.

The cargo OTV's have high specific impulse, about 8,000 seconds, but very low thrust. Accordingly, they require relatively little propellant to deliver the cargoes but take approximately six months for the uptrip. The personnel OTV's have high thrust requiring only a day for the trip each way but consume much more propellant relative to their transported payload.

The orbit transfer vehicles are based and serviced at the low earth orbit staging base with the exception of solar array annealing for the electric OTV which is done at geosynchronous orbit because of the availability of more nearly continuous sunlight for electric power to drive the annealers.

GEO Construction Concept
Electric Orbit Transfer Vehicles



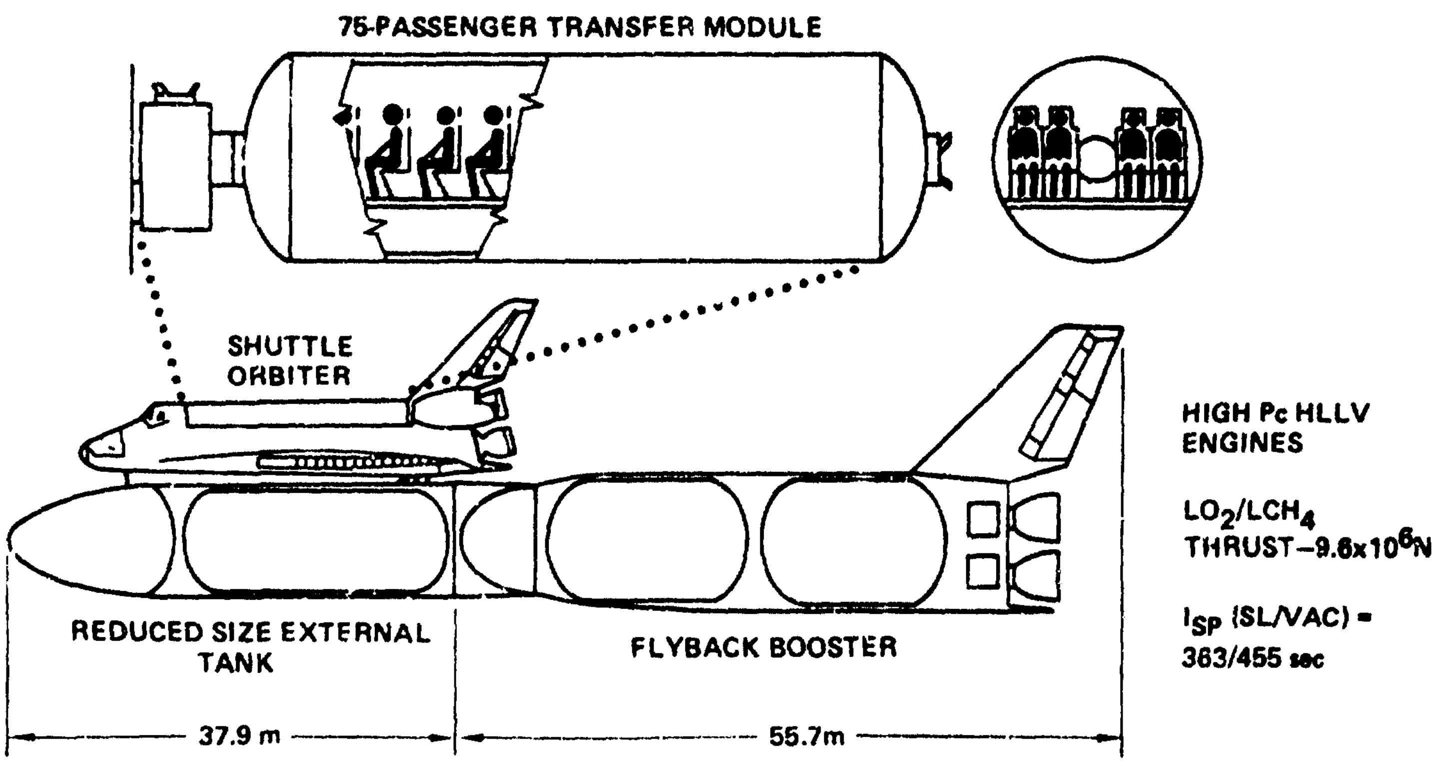
HEAVY LIFT LAUNCH VEHICLE

The accompanying illustration shows the reference heavy lift launch vehicle design. The gross payload is 400 metric tons to low earth orbit with an effective net payload of about 380 metric tons. Both stages are fully reusable. The liftoff weight is approximately 11,000 metric tons. The first stage employs liquid oxygen and liquid methane as propellants; the second stage employs liquid oxygen and liquid hydrogen. The payload bay is 17 meters in diameter by 23 meters in length. The first stage employs air-breathing engines for fly-back to the launch site.

PERSONNEL LAUNCH VEHICLE

Illustrated here is the assumed modification to the present space shuttle for SPS personnel transport. Modifications include a passenger module for the payload bay and a fly back liquid propellant booster to replace the solid boosters in the first stage.

Personnel Launch Vehicle



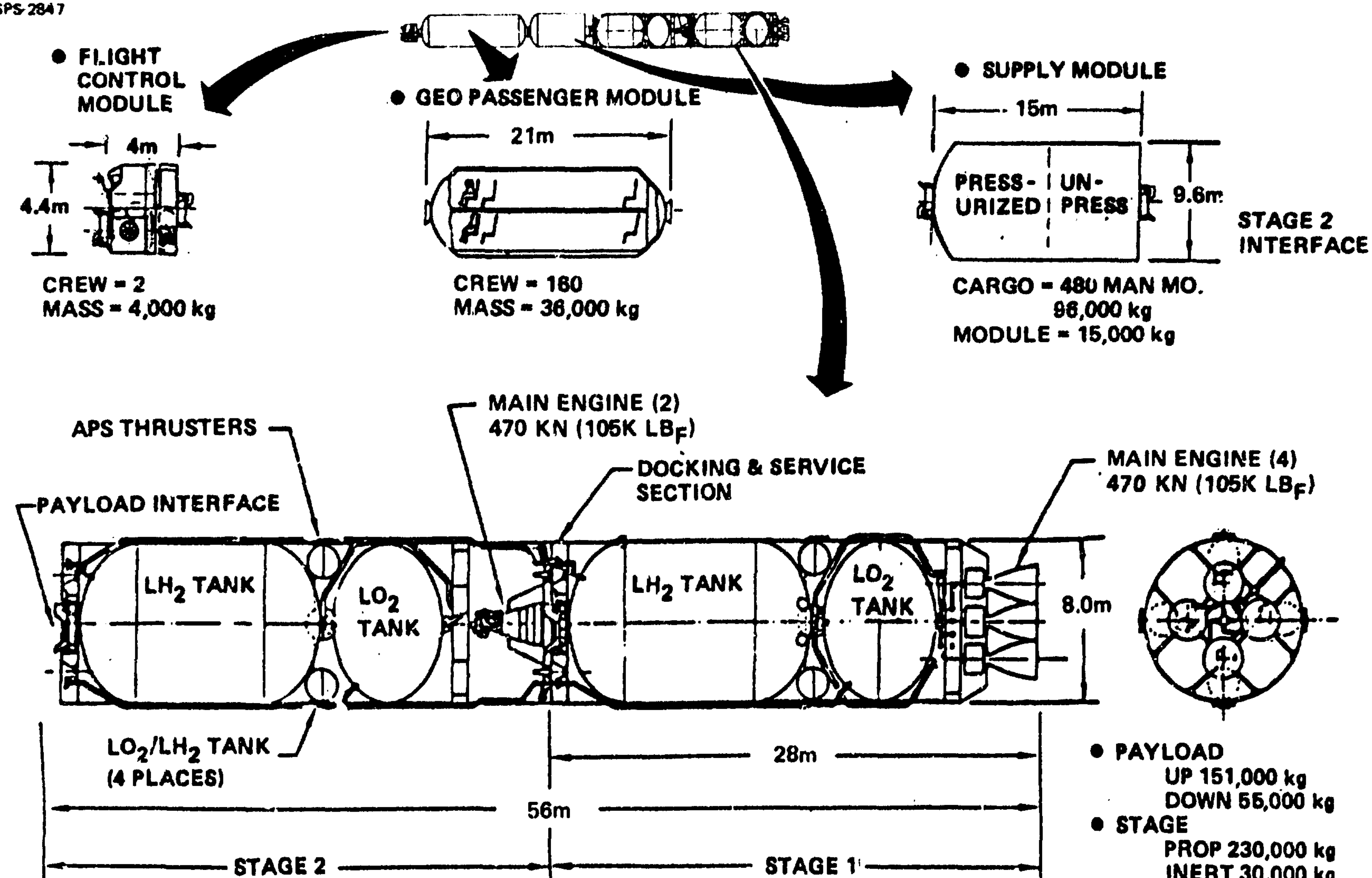
LO2/LH2 COMMON STAGE OTV

The personnel orbit transfer vehicle is shown here in additional detail. Payload provisions include a flight control module for OTV pilots, a passenger module for 160 passengers, and a supply module which delivers sufficient crew and base maintenance supplies for the 160 people for 90 days. The propulsion system is a two stage vehicle with the airframes of the two stages being identical. The first stage is a booster stage that provides most of the transfer impulse for the initial transfer to geosynchronous transfer orbit. This booster stage is then recovered in low earth orbit for the next mission. The upper stage circularizes at geosynchronous orbit, rendezvous and docks with the GEO construction base, transfers crew and supplies and then returns to low earth orbit. The mission delta V split is adjusted so that the propellant capacity of each stage is fully utilized.

LOX/LH_2 Common Stage POTV

BOEING

SPS-2847



EOTV CONFIGURATION

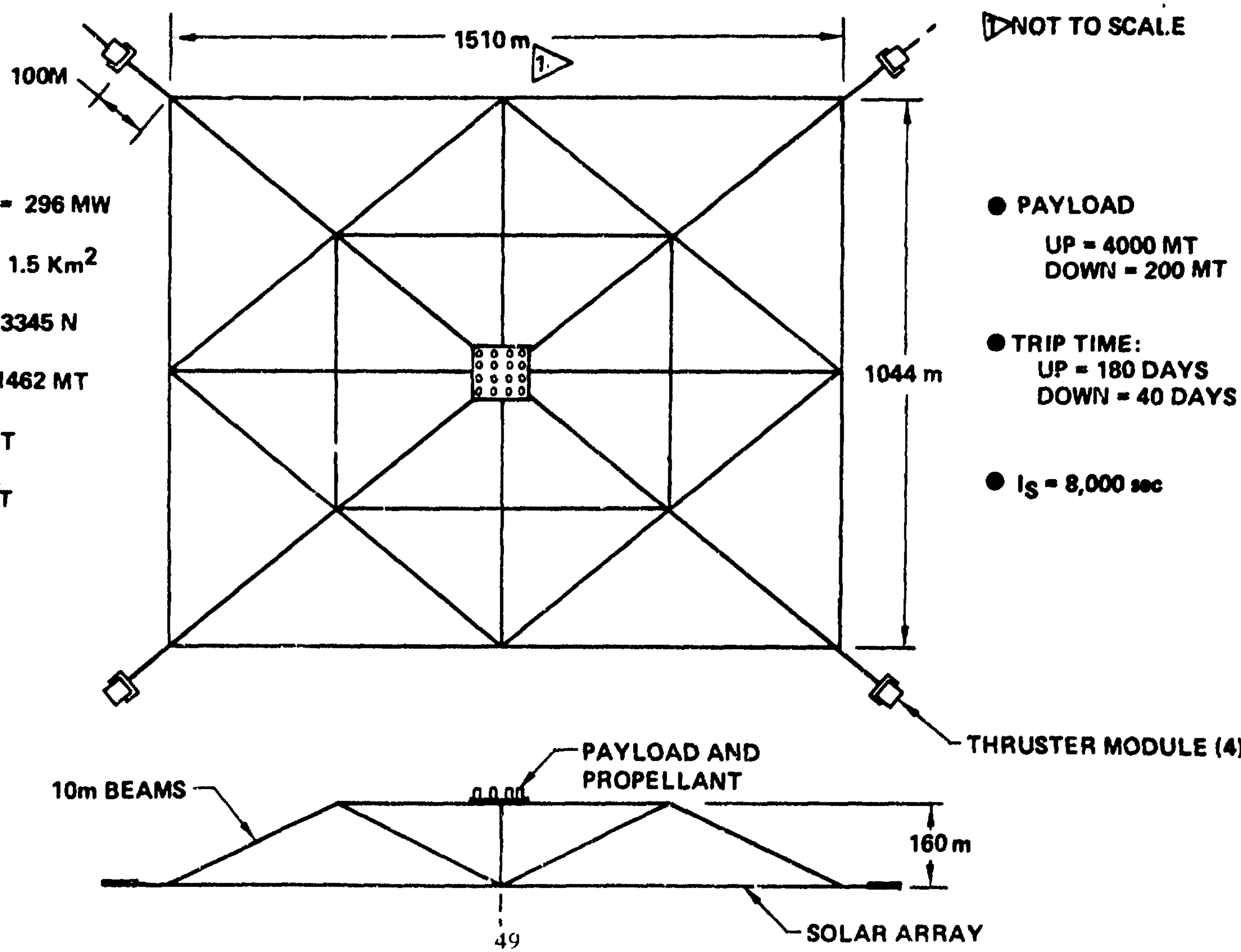
The independent electric OTV configuration shown here is updated from earlier mid-term data. Mass and size increases resulted from incorporation of bussing losses in the power budget and correction of other analysis approximations used in the earlier effort. This orbit transfer vehicle is sized to deliver 4,000 metric tons to geosynchronous orbit and return with 200 metric tons. The return payload capability provides for return of packaging equipment and other items from the geosynchronous orbit construction site. Because the electric orbit transfer vehicle is smaller than the SPS modules discussed on the previous page, it suffers comparatively little from performance losses induced by gravity gradients.

SPS

Electric OTV Configuration Update

BOEING

SPS-2423A



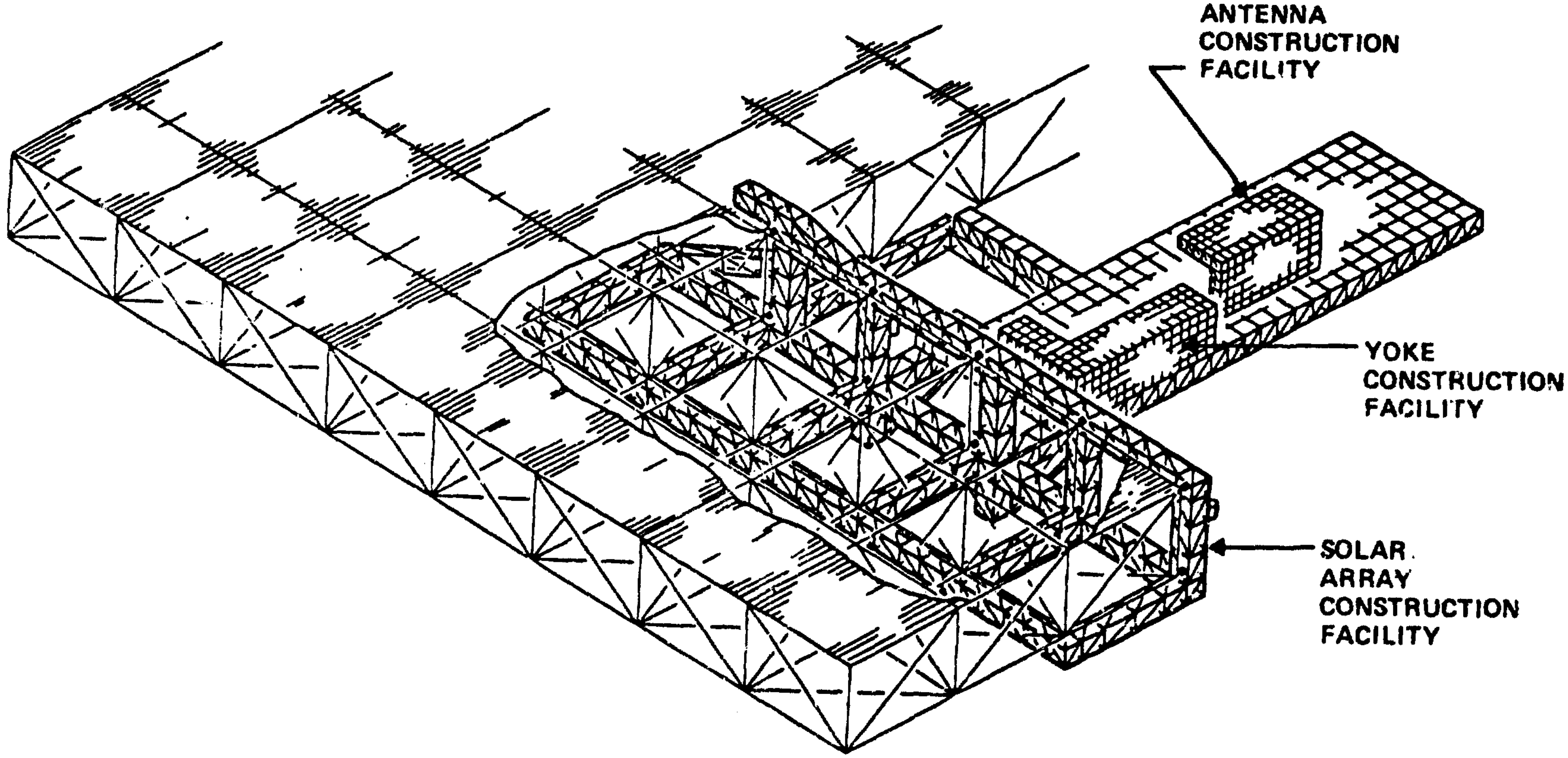
- INITIAL POWER = 296 MW
- ARRAY AREA = 1.5 Km^2
- ELEC THRUST = 3345 N
- EMPTY MASS = 1462 MT
- ARGON = 469 MT
- LO_2/LH_2 = 46 MT

- PAYLOAD
  UP = 4000 MT
  DOWN = 200 MT
- TRIP TIME:
  UP = 180 DAYS
  DOWN = 40 DAYS
- I_S = 8,000 sec

CONSTRUCTION BASE END BUILDER DESIGN

The current reference construction base is the four-bay end builder illustrated here. This system builds the 8-by-16-bay SPS solar array support structure in two passes, deploying solar arrays and other equipment at the same time. Concurrently, the antenna and yoke are constructed in the facilities shown. When all are completed they are joined together to form the SPS. This construction base operates in geosynchronous orbit.

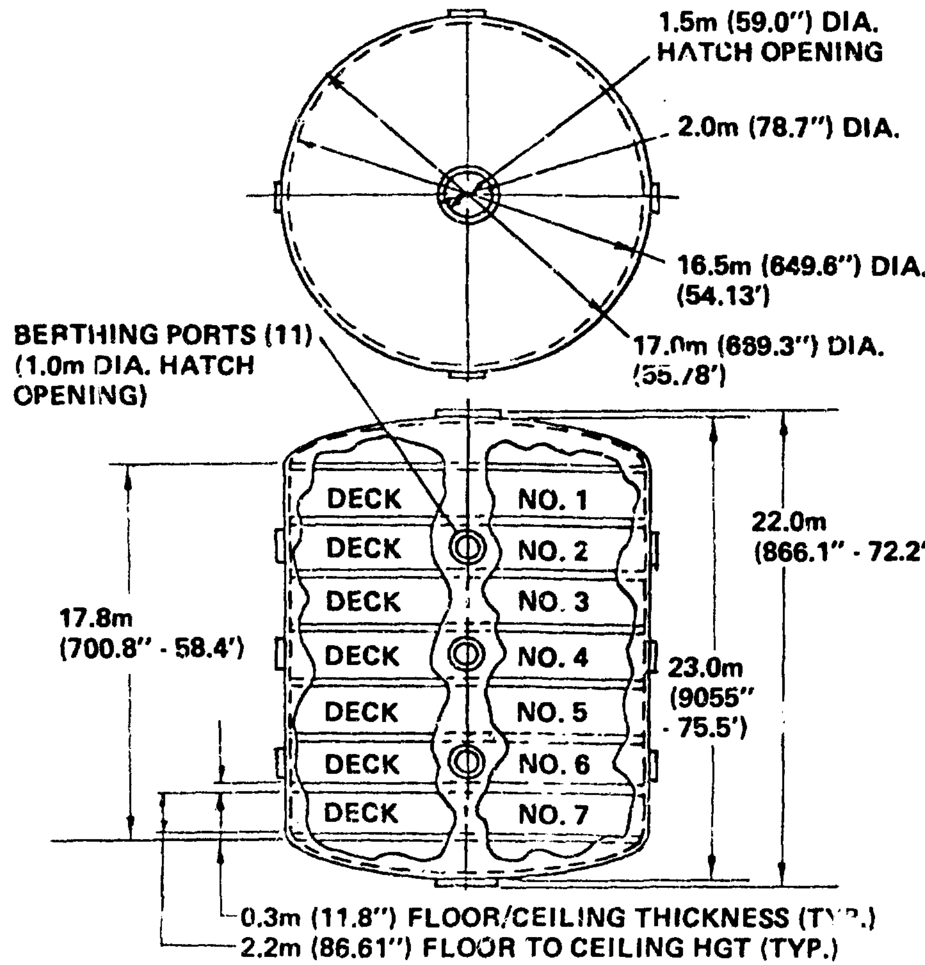
Construction Base End-Builder Design



CREW MODULE SIZED FOR 100

The crew complement for the base is approx ately 400 construction workers including support personnel. Illustrated here are major features of one of four crew habitat modules that make up part of the base shown on the previous figure.

Crew Module Sized For 100



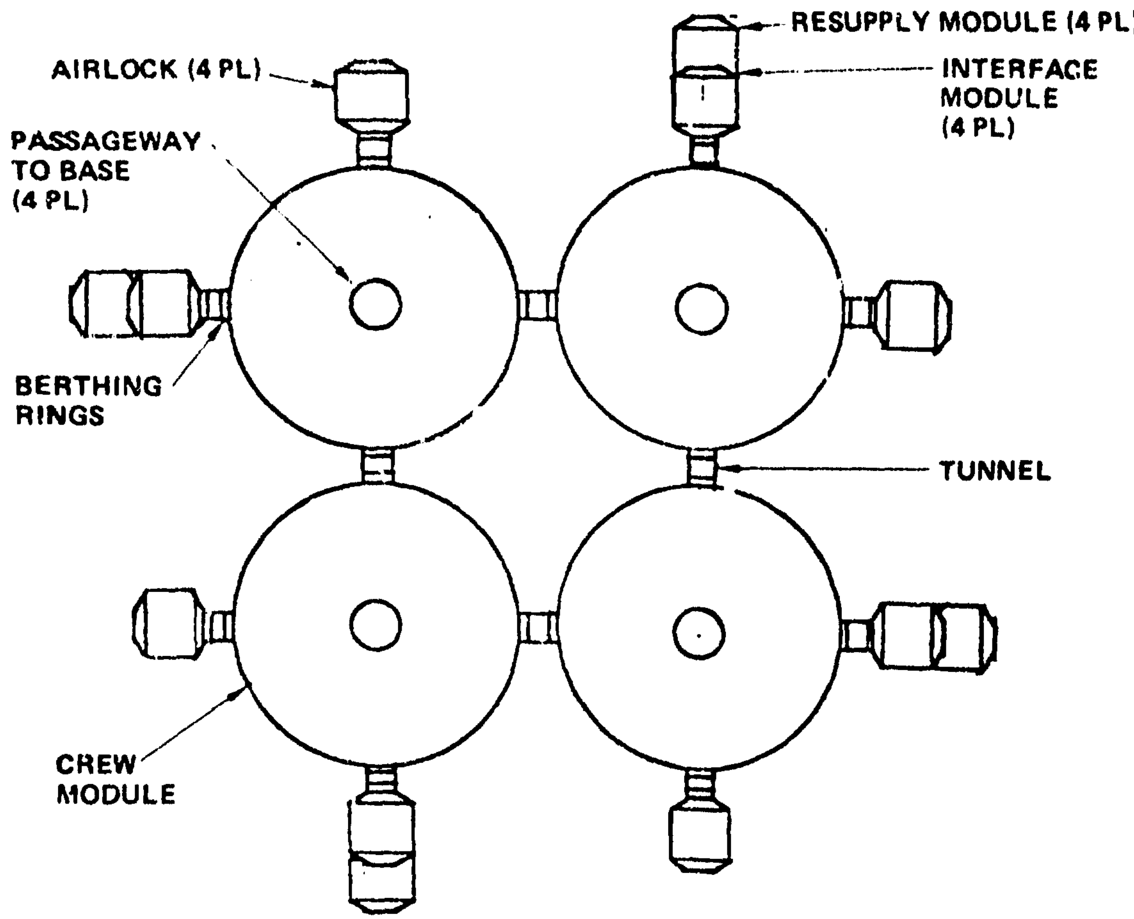
BASE CONSTRUCTION CREW HABITAT / WORK STATION COMPLEX

The assembly of four crew modules that comprise the crew habitat area for the construction base is illustrated.

Base Construction Crew Habitat/ Work Station Complex

SPS-2918

BOEING

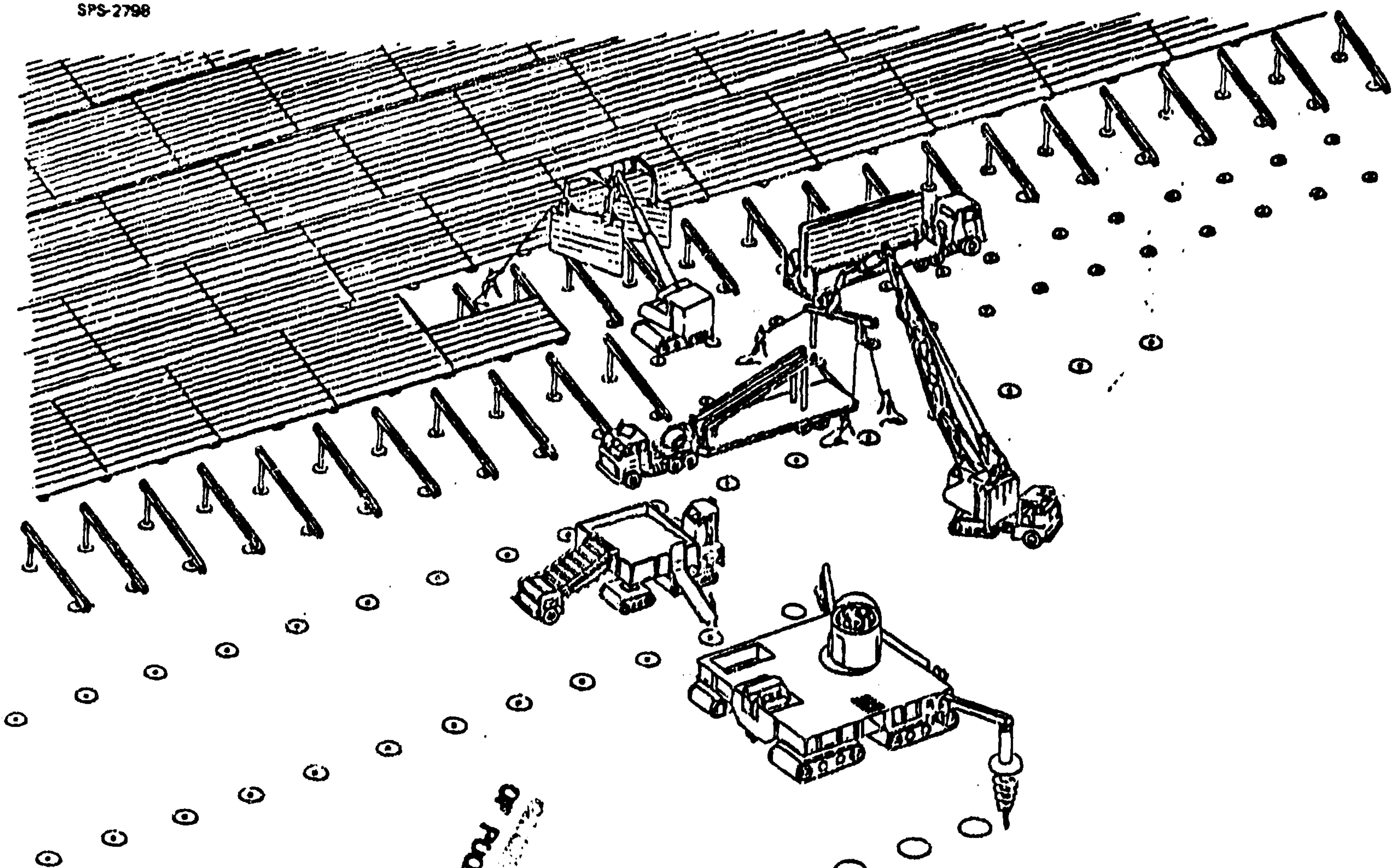


5-GIGAWATT RECTENNA CONSTRUCTION CONCEPT

As a part of the current study, General Electric analyzed rectenna construction with the objective of defining a mechanization and structural concept that could reduce rectenna costs from the earlier estimates. A pictorial summary of the construction concept is illustrated here. The basic support structure is steel reinforced concrete. This support structure is emplaced by construction equipment employing advanced technology location systems to allow precise location of the footings. Support and rectenna panels are manufactured at the site in portable factory buildings and moved for installation as illustrated.

Five GW Rectenna Construction Concept

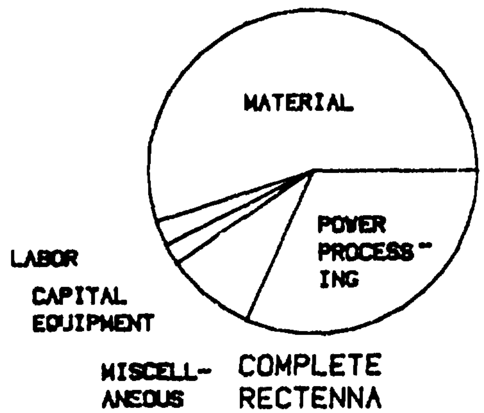
SPS-2798



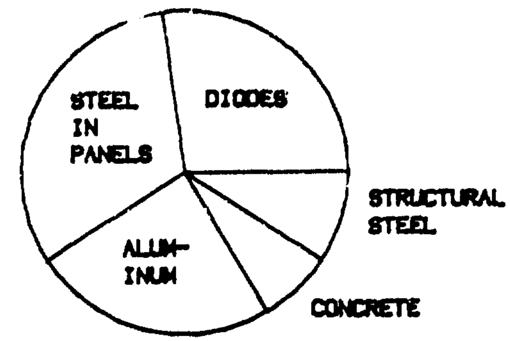
RECTENNA COST DISTRIBUTION

The cost for one rectenna was estimated as slightly in excess of two billion dollars. The cost distribution is shown. The mechanization developed by General Electric succeeded in eliminating most cost excepting for materials and for the power processing systems that interfaces the rectenna dc electricity to a power grid. The chart also illustrates the breakout of materials, labor and equipment costs according to rectenna elements.

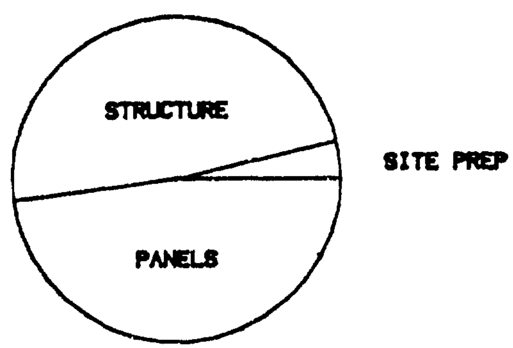
RECTENNA COST DISTRIBUTION



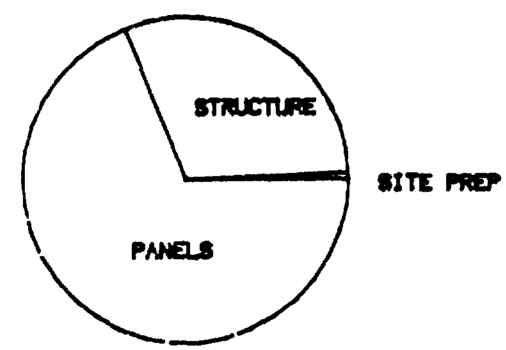
COMPLETE RECTENNA



MATERIALS



LABOR



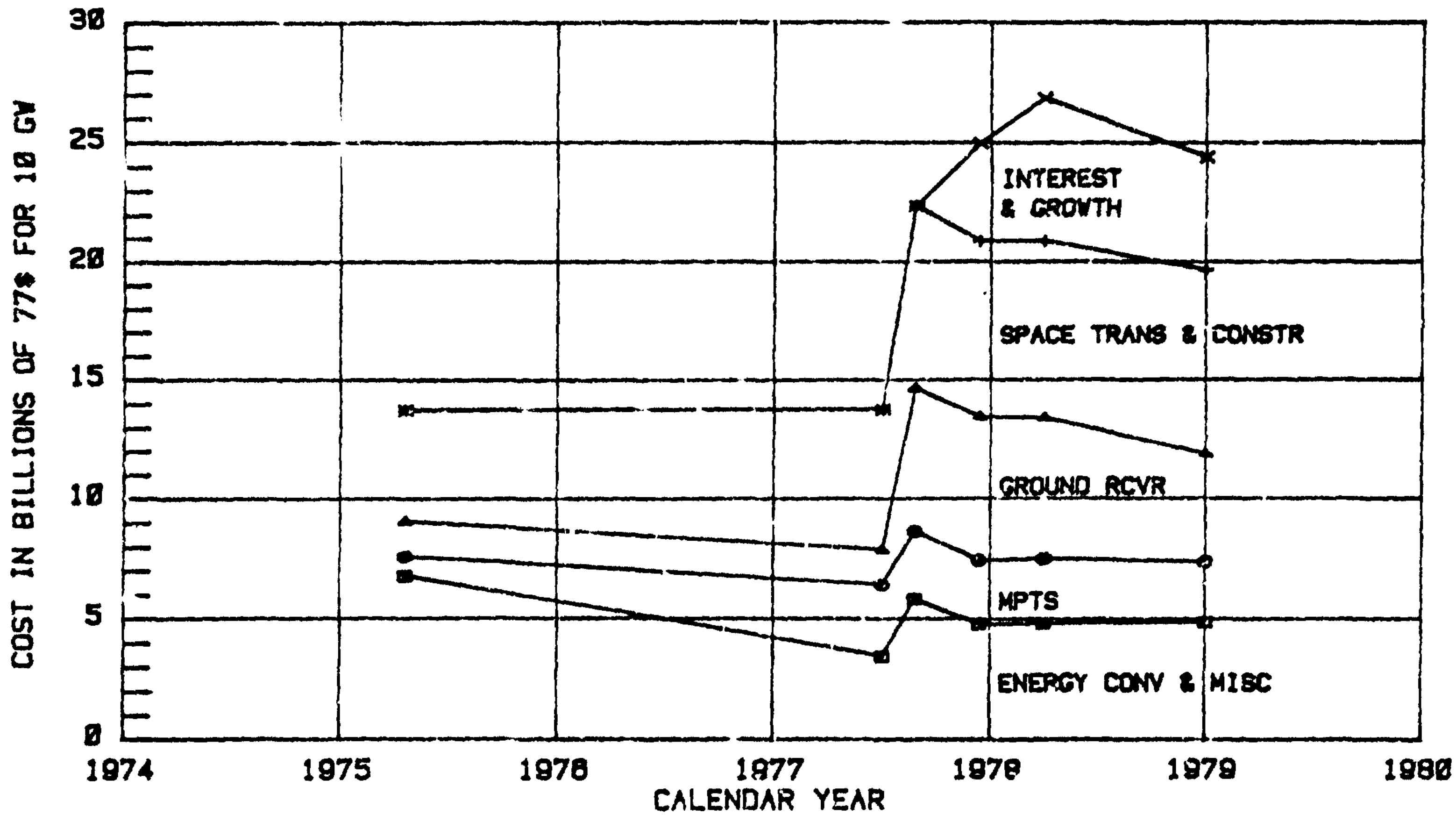
EQUIPMENT

SPS COST ESTIMATE HISTORY

Shown on the facing page is the cost estimate history analogous to the mass estimate history shown earlier. Not all of the mass reference points were accompanied by a cost statement. The most striking change in cost estimates has been in the recognition of relatively high costs for the ground receiver and the allocation of interest and growth allowances in the cost statement, analogous to the growth allowance carried in the mass statement.

SPS Reccuring Cost Estimate History

SPS-2823



SOLID STATE SPS SUMMARY

The solid state discussion covers the four items tabulated.

Solid State SPS Summary

- MICROWAVE ALTERNATIVES
- WHY SOLID STATE?
- SANDWICH CONFIGURATION
- ANTENNA-MOUNTED SOLID-STATE CONFIGURATION

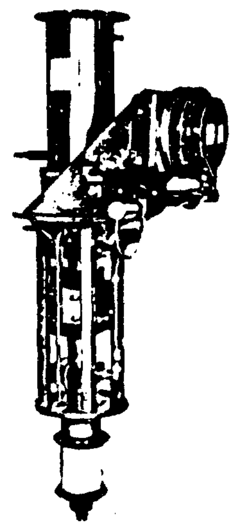
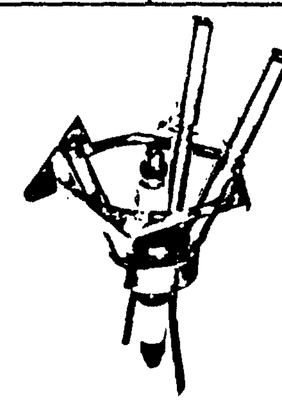
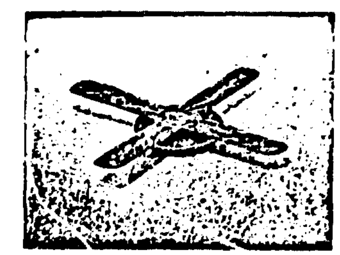
DC RF CONVERTER FEATURES

The three principal DC to RF converter systems that have been considered for SPS application are the klystron, crossed-field amplifier and the solid state transistor. Klystrons have received most of the emphasis in past systems definition studies. Current emphasis is being directed to solid state systems.

BOEING SPS

DC-RF Converter Features

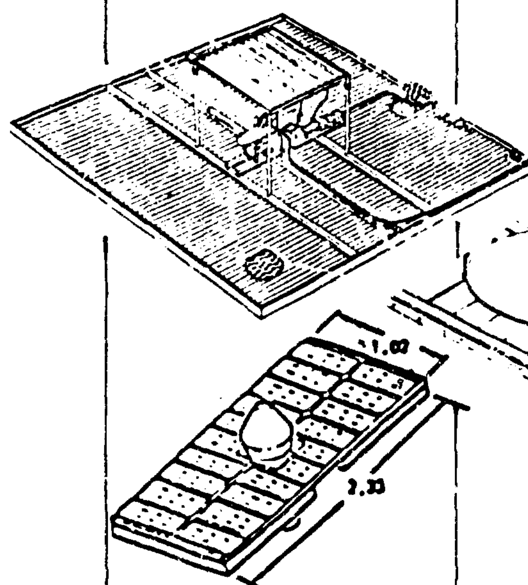
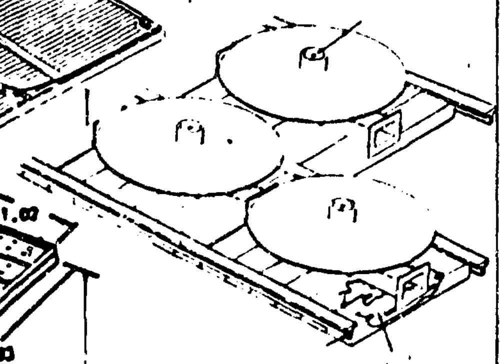
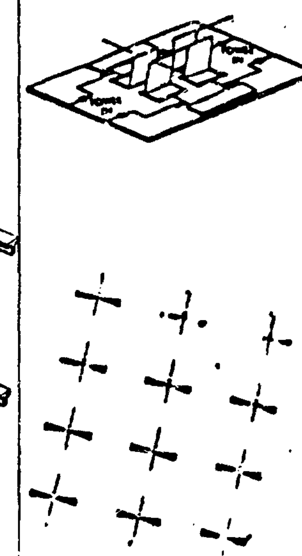
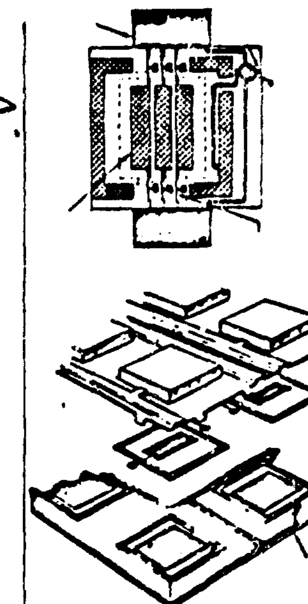
79-200

DEVICE ⇨	KLYSTRON	CROSSED FIELD AMPLIFIER		SOLID STATE TRANSISTOR
PROPERTY ⇩		AMPLITRON	INJECTION LOCKED MAGNETRON	FET
				
POWER (CW)	50-70 KW	5 KW		1-5 WATTS
VOLTAGE	40 Kv	<20 Kv		10-20 V
EFFICIENCY	>80%	>85%		75%
MTBF (1985)	>10 YEARS	>10 YEARS		>>100 YEARS
NO. OF OUTPUT DEVICES PER ANTENNA	10^5	10^6		$>10^9$
TEMPERATURE	300-500°C	300-500°C		100-130°C
CATHODE	THERMIONIC	COLD OR THERMIONIC		NONE
SATURATION GAIN	40db	<10 db		10 db

RF MODULE OPTIONS

The three types of RF converters lead to three types of module options with two variations shown in the solid state area. The Klystron lends itself well to radiating through a slotted wave-guide array antenna as does the crossed field amplifer. Since solid-state amplifiers are equal to or less than in power than a single radiating slot, it is more logical to employ solid state devices driving a dipole billboard or combiner-circuit microstrip cavity radiators.

RF Module Options

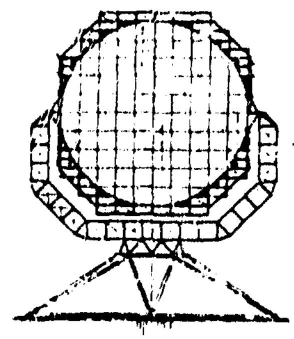
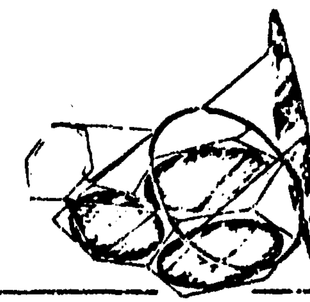
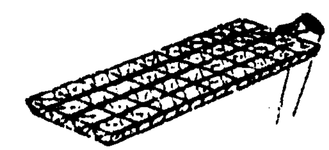
MODULE TYPE	KLYSTRON	CFA	SOLID STATE	
				
RF RADIATOR	SLOTTED WAVEGUIDE CAVITY RESONATOR	SLOTTED WAVEGUIDE	DIPOLE BILLBOARD	MICROSTRIP CAVITY
THERMAL DESIGN	ACTIVE COOLING HEAT PIPE OR PUMPED FLUID	PASSIVE COOLING PYROLITIC GRAPHITE	PASSIVE COOLING (<150°C)	
MAX RF POWER DENSITY	22 Kv/m^2 (η = 85%)	22 kw/m^2 (η · 90%)	5 Kw/m^2 (η = 80%)	

SPS RF DESIGN OPTIONS

Most SPS designs to the present time have employed antenna mounted transmitters as for the reference design. Other concepts that have been investigated have attempted to solve the power distribution problem for low voltage solid state systems by either a sandwich approach where the solid state transmitter is integrated with the solar array or by an RF reflector approach for which the solid state transmitters are again close to the solar array with power being distributed by high power waveguides.

BOEING SPS

SPS RF Design Options

RF CONVERTER →	ANTENNA MOUNTED		SOLAR CELL MOUNTED (CONCENTRATION RATIO ≈ 3)	
SPS DESIGN ↓			OPTICAL REFLECTOR 	RF REFLECTOR 
	KLYSTRON OR CFA	SOLID STATE	SOLID STATE	SOLID STATE
POWER OUTPUT TO GRID	5 GW	2 GW	0.7 GW	0.2 GW per km^2 SOLAR CELLS
SPACE ANTENNA DIAMETER	1 km	1.5 km	2.7 km	HIGH POWER WAVEGUIDE
RECTENNA DIAMETER @ 23 mw/cm^2	10 km	6.7 km	3.8 km	NOT DETERMINED
ANTENNA	10 db TAPER	10 db TAPER	UNIFORM	ADVANCED HORN FED PARABOLOID

WHY SOLID STATE?

The principal motivator for the solid state system is the much greater projected reliability than is expected for vacuum tube devices. The device mean-time-between-failure may be as much as two orders of magnitude better than vacuum tube devices. Further, lower mass per unit area is expected, and research and development activities may be conducted with small hardware items that can be quickly modified, tested, improved and retested.

However, there are certain problems associated with the solid state system. They are low-temperature, low-voltage, and low-power devices. The efficiency is somewhat uncertain, the cost of high performance devices is today high, and the complexity of the solid state transmitter appears to be greater.

Presently on-going system study efforts are attempting to trade off these advantages versus disadvantages to arrive at practical approaches for employing solid state transmitters, and more importantly, to arrive at the most relevant research objectives and approaches.

Why Solid-State?

SPS-2831

- RELIABILITY
- LOWER MASS/AREA
- DEVELOPMENT ON SMALL HARDWARE ITEMS

BUT

- TEMPERATURE LIMITS
- LOW VOLTAGE, LOW POWER
- EFFICIENCY?
- COST??
- COMPLEXITY??

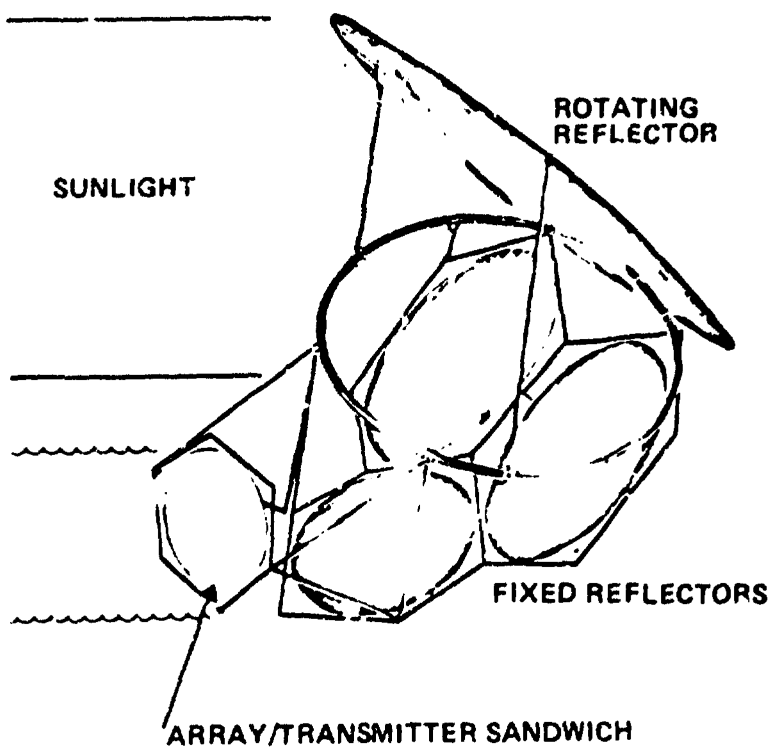
THE SOLAR CELL SOLID STATE SANDWICH SPS CONCEPT

The sandwich concept has been proposed as a way of solving some of the problems attendant to solid state application. Advantages and problems are indicated on the facing page.

The basic concept is to use a mechanical joint with a reflector configuration in order to the sun so that the solar array itself need not face the sun and can be integrated with the transmitter facing the earth. The configuration shown achieves a geometric concentration ratio of 3 and an actual achieved concentration of roughly 2 suns.

The Solar Cell Solid-State Sandwich SPS Concept

SPS-2696



ADVANTAGES

- ELIMINATES POWER DISTRIBUTION & PROCESSING (AT LEAST MOST OF IT)
- ELIMINATES HIGH VOLTAGES
- ELIMINATES ELECTRICAL ROTARY JOINT
- MAY BE ADAPTABLE TO LARGE APERTURE, LOW POWER SYSTEMS

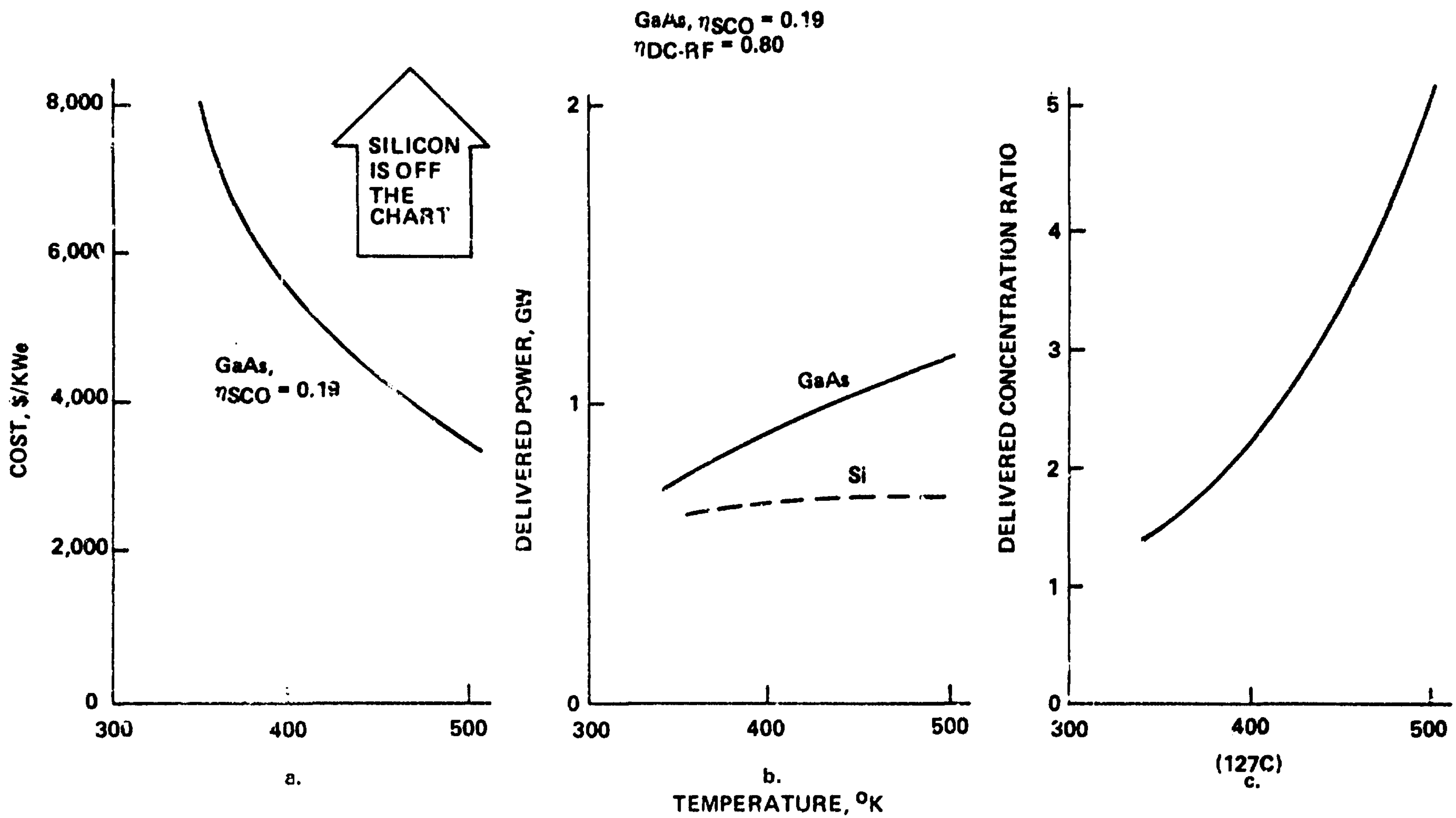
PROBLEMS

- THERMALLY-CONSTRAINED DESIGN
- HOW TO IMPLEMENT ILLUMINATION TAPER?
- MECHANICALLY & STRUCTURALLY COMPLICATED, HARD TO CONSTRUCT?

PERFORMANCE VERSUS SANDWICH TEMPERATURE

Integration of the solar array and the transmitter combines the thermal rejection problem of the solar array with the thermal rejection problem of the transmitter. The design is basically thermally constrained. Parametrics were developed to evaluate the configuration based on the assumed operating temperature for the transmitter and the solar array. It is believed that the maximum feasible operating temperature consistent with long life for the solid state devices is approximately $400^{\circ}K$. Silicon solar arrays do not perform at all well in this configuration because of their somewhat lower efficiency and their rapid output degradation with increasing temperature.

Performance vs Sandwich Temperature



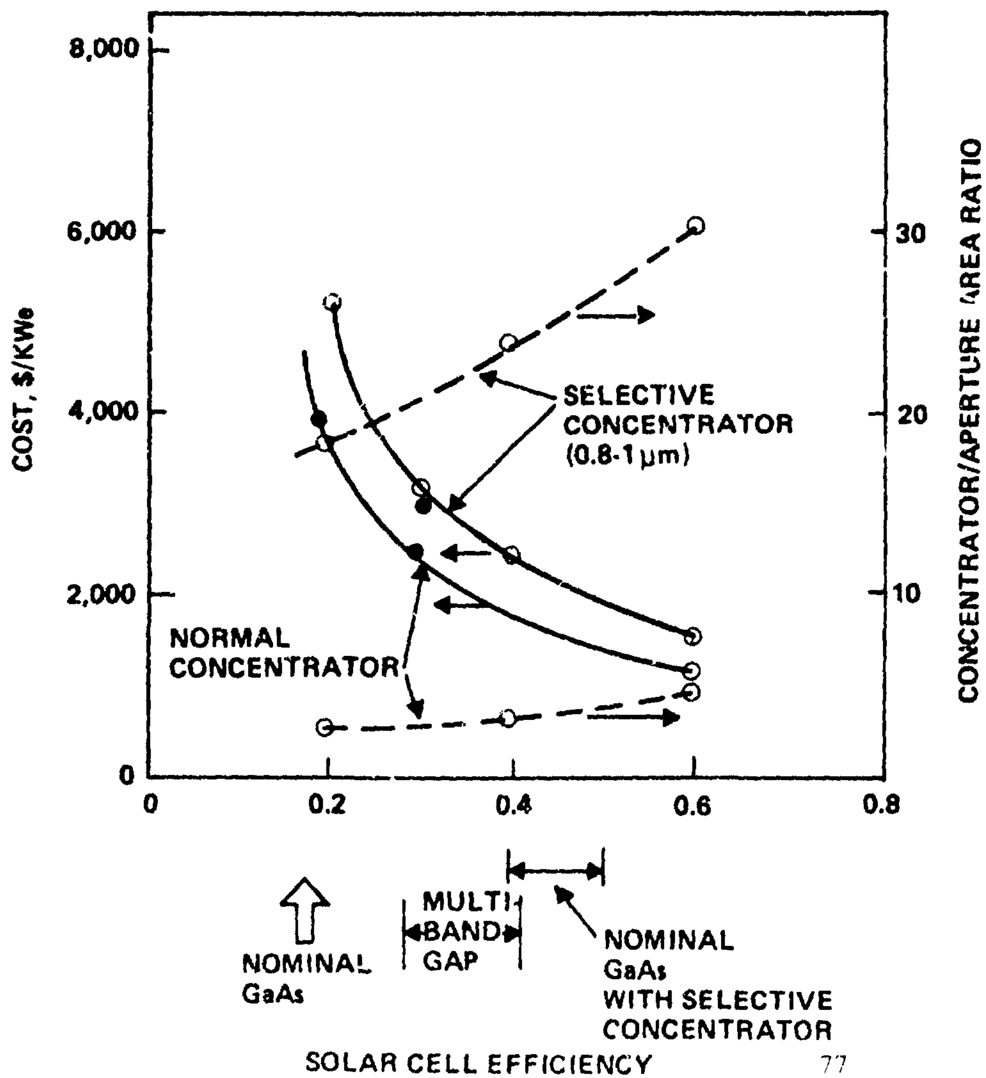
PERFORMANCE VERSUS SOLAR CELL EFFICIENCY

If the solar cell efficiency could somehow be improved, the thermal constraints would be eased somewhat and the matchup of solar array area to transmitter area would be improved. Parametric results are shown here. Two approaches to high solar cell efficiency have been discussed. One would employ multiple band gap solar cells. These curves are marked "normal concentrator". A second approach is to use a selective concentrator which reflects to the solar cells only the portion of the solar spectrum that they can effectively use. This could cause an ordinary gallium arsenide solar cell to operate at an efficiency approaching 50%. These curves are marked "selective concentrator". Because the selective concentrator is very inefficient, a much larger concentrator area is required to achieve an effective concentration ratio of 3 to 5. The geometry problem attendant to the large area selective concentrator is indicated at the right hand part of the figure.

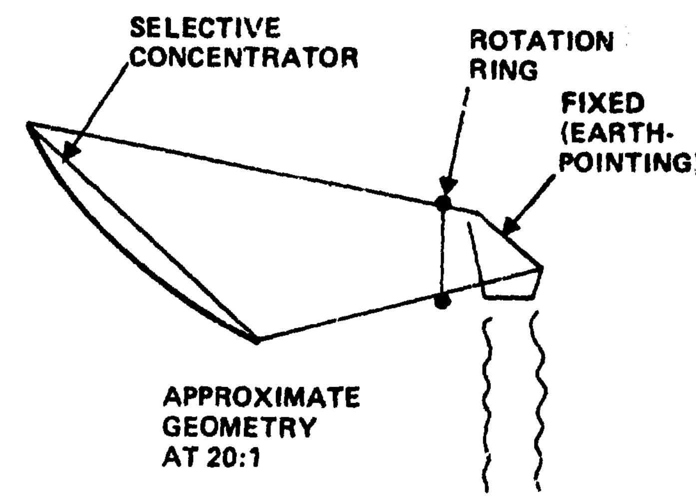
Performance vs Solar Cell Efficiency

SPS-2693

(a)



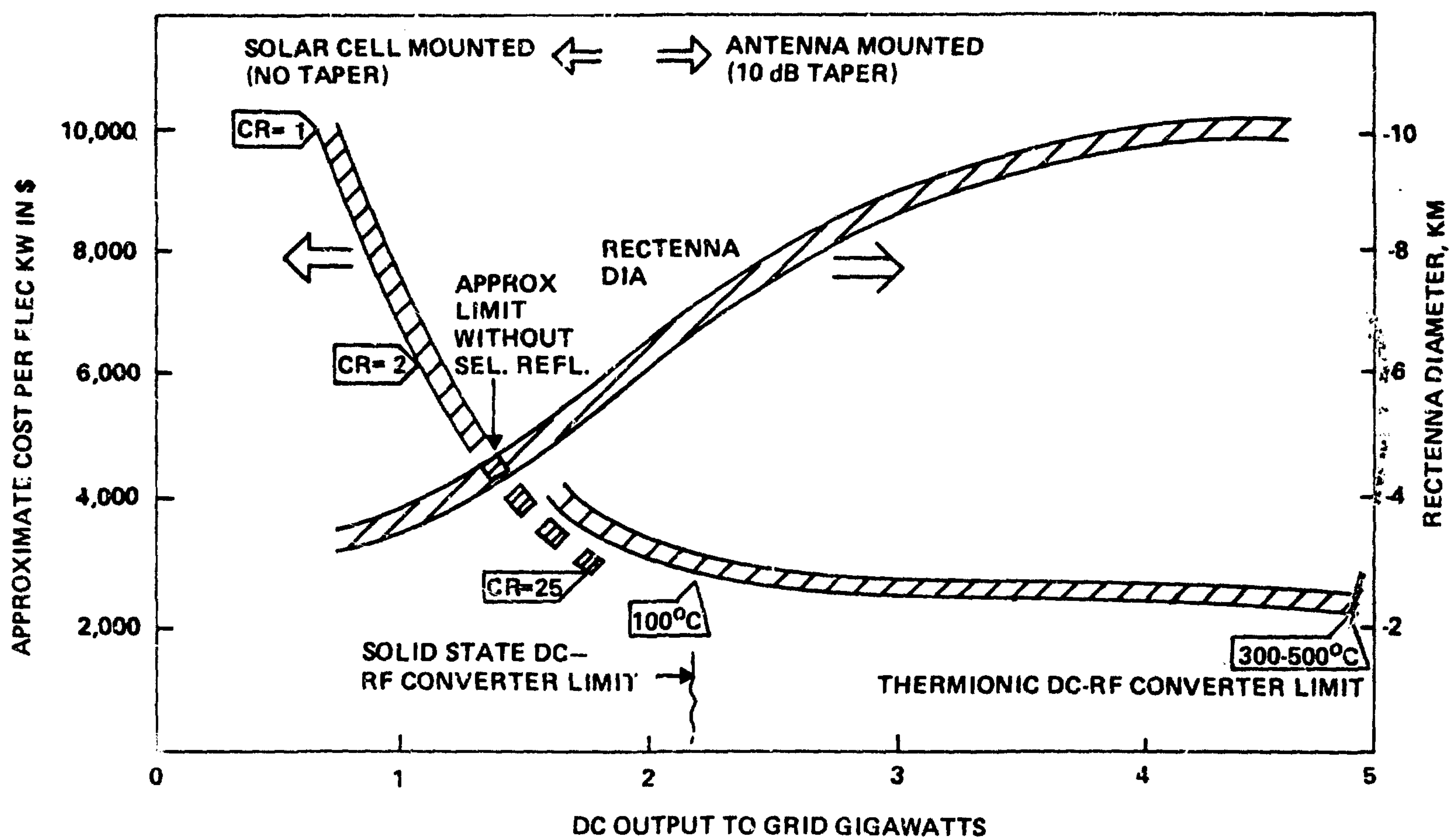
(b)



SPS COST TRENDS

The sandwich configuration appears to trend very similarly to the antenna baseline configurations. The sandwich appears to trend below the baseline only when advanced technologies such as very high efficiency solar cells or selective reflectors are employed. These kinds of technologies, however, would also improve the cost performance of the reference systems.

SPS Cost Trends



SANDWICH CONCLUSIONS

The sandwich configuration may prove attractive for very low power SPSs provided that the mechanical complexity issues can be resolved. The sandwich requires a very large mechanical rotating joint, kilometers in diameter, and its configuration is typical of those 3 dimensional configurations that have proven difficult to construct in space.

The sandwich does not appear to be a configurational breakthrough leading to low cost. It appears to fall on a cost-versus-power trend line.

Sandwich Conclusions

- MAY BE BETTER LOW-POWER CONFIGURATION THAN ANTENNA-MOUNTED IF MECHANICAL COMPLEXITY ISSUES CAN BE RESOLVED

- APPEARS TO FALL ON COST VS POWER TREND LINE; NO INHERENT COST ADVANTAGE

MODULE CONCEPT

Most of the Boeing investigation of solid state systems have been aimed at a solid state module with the objectives tabulated on the facing page.

Module Concept

SPS-2834

- ADAPTABLE TO ANTENNA-MOUNTED SYSTEM
- THERMALLY EFFICIENT
  - GOOD HEAT PATHS
  - RADIATE FROM BOTH SIDES
- EFFICIENT COMBINING OF LOW-POWER ($\approx$5-WATT) DEVICES
  - ATTAINS ADEQUATE POWER DENSITY
- HIGH GAIN, PHASE-STABILIZED

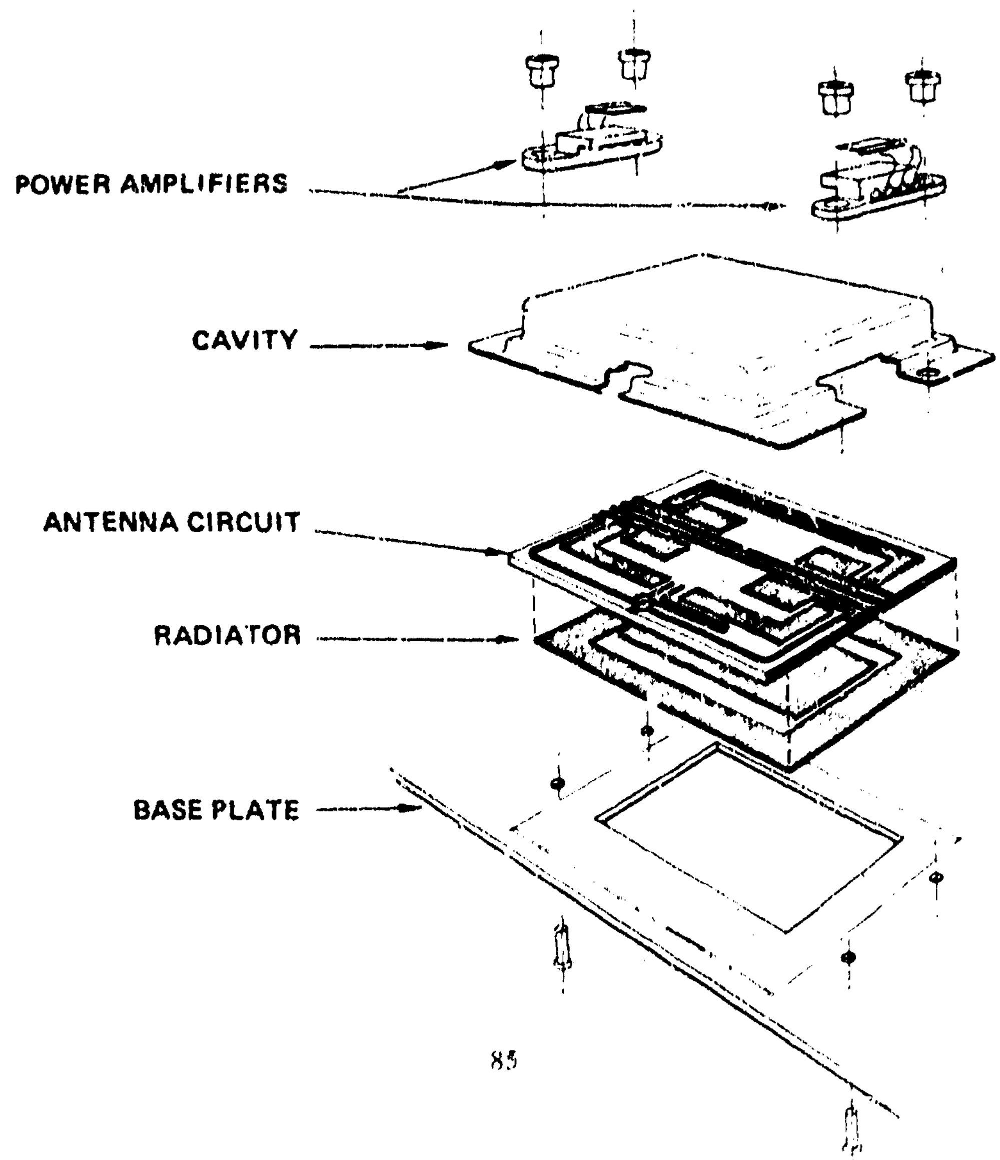
SOLID STATE COMBINER RADIATOR MODULE

The main features of the combiner radiator module are illustrated on this chart. The antenna circuit itself is capacitively coupled to the radiator patch through a ceramic dielectric. The radiator patch functions as a double slot, emitting linearly polarized RF radiation. The antenna circuit is driven by a pair of push-pull power amplifiers employing 5 watt gallium arsenide FET transistors in each of the four final output stages. DC supply connections are routed through the center of the antenna along the zero potential line. Output from the radiator is compared to the input RF drive signal by a phase comparator circuit and the phase of the RF drive to the amplifiers is adjusted accordingly to maintain phase control of each individual radiator. This compensates for through phase variations in the power amplifiers and antenna circuitry. The antenna is covered by a resonant cavity which provides filtering at the amplifier outputs. The entire assembly is mounted to an aluminum baseplate and ground plane.

BOEING SPS

Solid State Combiner-Radiator Module

SPS-2836



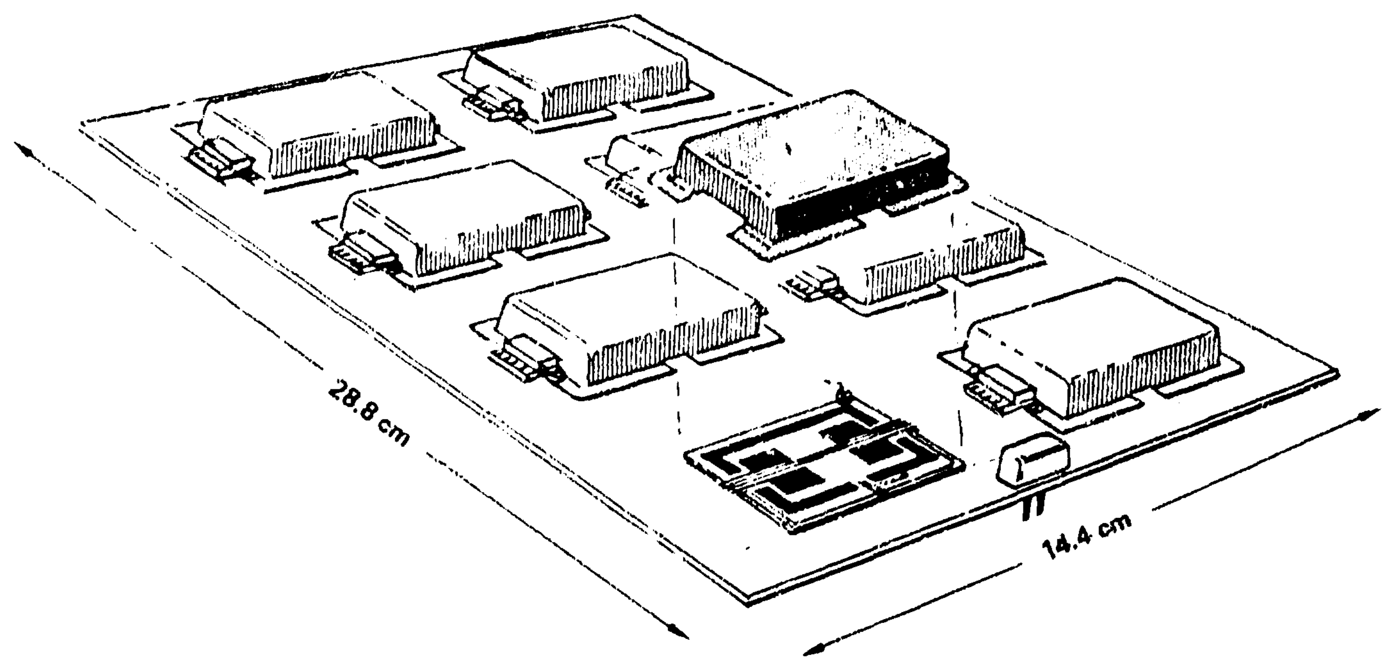
INTEGRATION OF MODULES INTO ANTENNA PANEL

The modules would be integrated into an antenna panel as illustrated here. The dimensions give an idea of the size of these modules. Each module radiates about 30 watts of linearly polarized RF power. Experiments have indicated that this module design provides a very low loss means of combining the output of 4 solid state power amplifiers. The module also includes phase correction feedback to phase stabilize the amplifiers and a fault detection system to substitute a load resistor for any amplifier that open circuits.

BOEING SPS

Integration of Modules into Antenna Panel

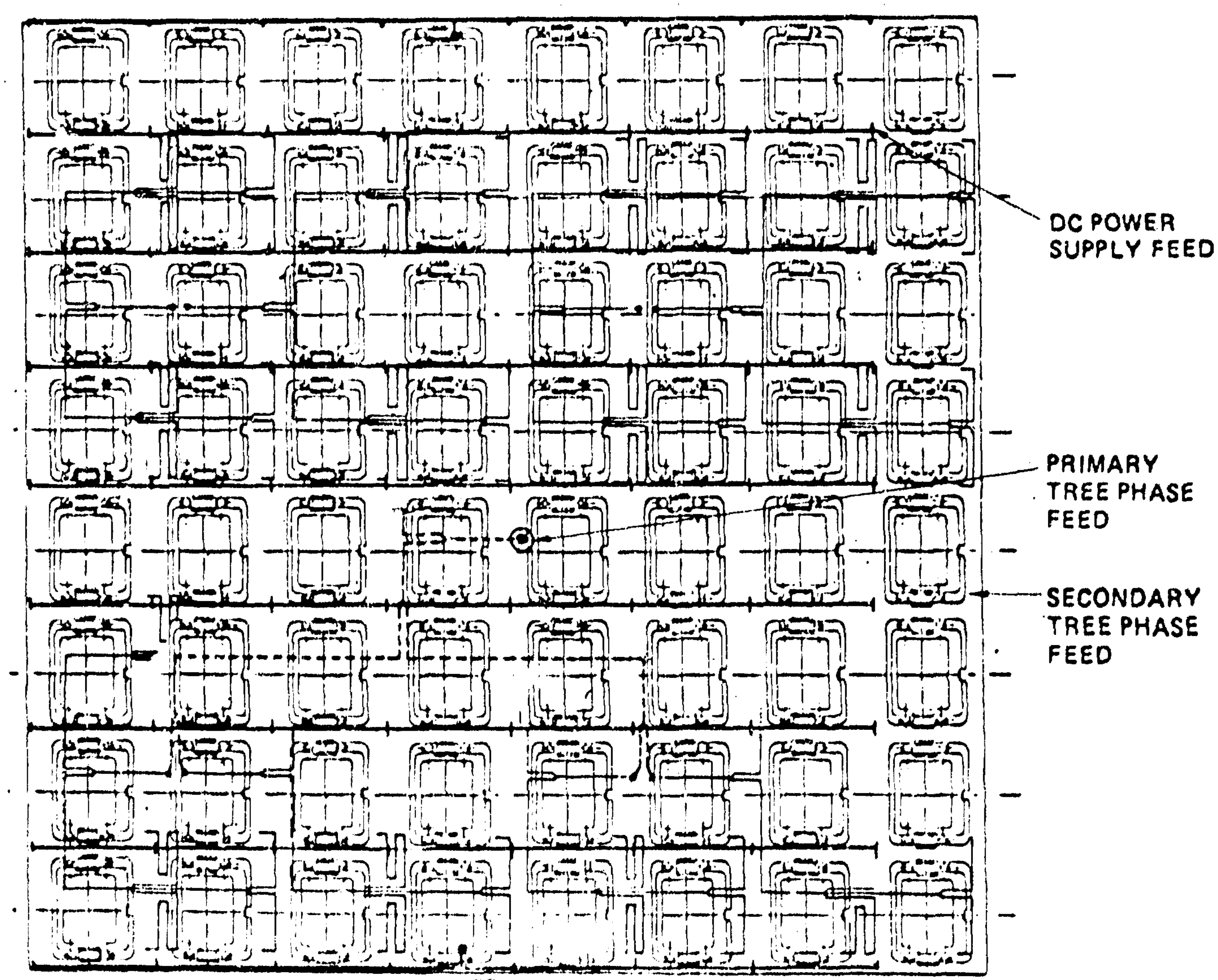
SPS-2837



64 MODULE PANEL LAYOUT

Illustrated on the facing page is the layout of basic panel including 64 solid-state combiner modules. A fiber optic phase-feed goes into the center of this panel where a pre-amplifier converts the fiber-optic phase signal to a microwave signal which is then distributed by the phase distribution network shown. This network at this level is presently conceived as open-loop. Further analysis and experiment will be necessary to ascertain to what degree open loop phase-feed can be employed with solid-state systems.

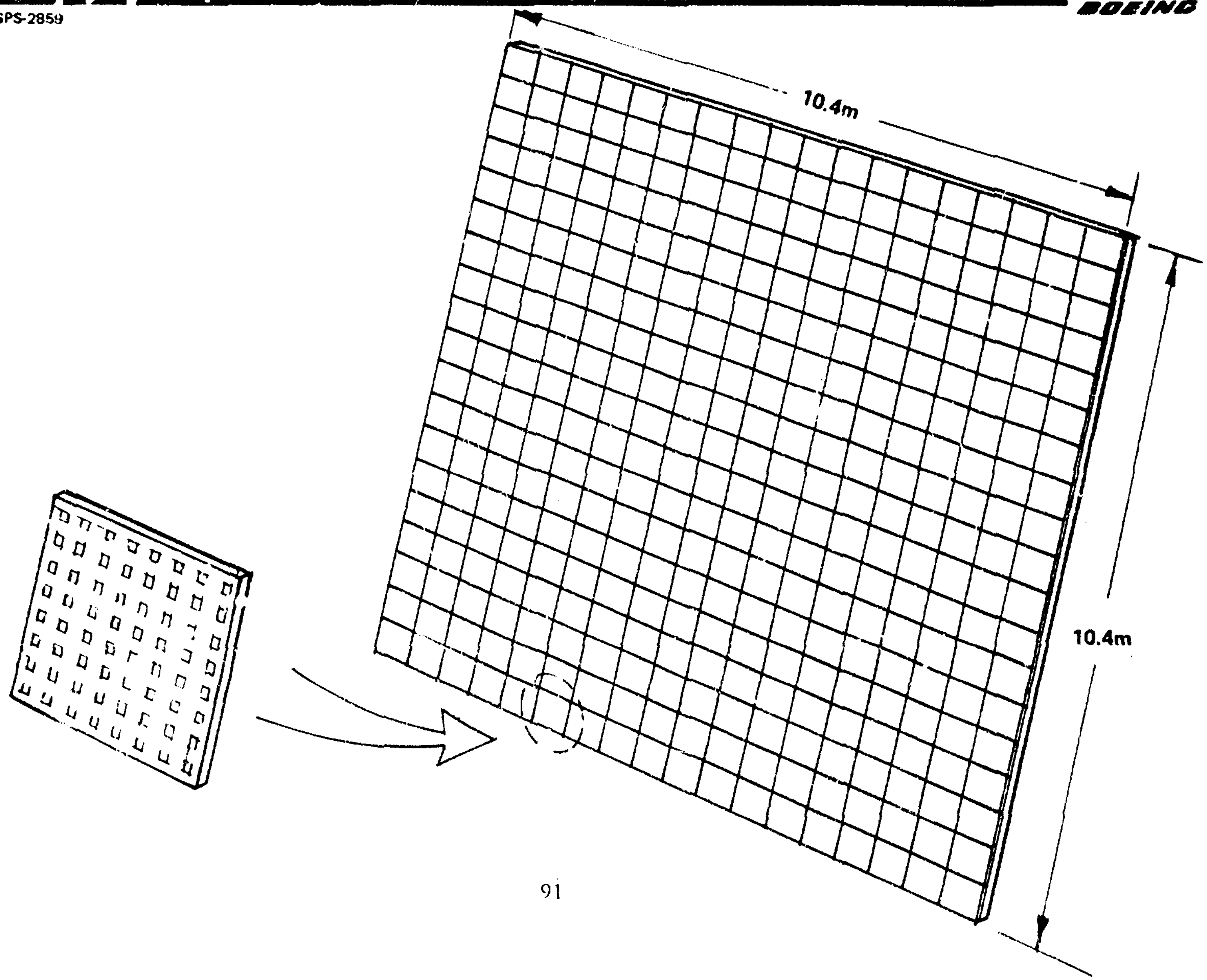
64-Module Panel Layout



SUBARRAY ASSEMBLY

A mechanical subarray includes 324 of the panels illustrated on the previous charts. The subarray will include four phase control receivers, one for each 5-by-5 meter subsection of the subarray. These phase control receivers will generate the local phase signal. This signal is distributed to the panel level by fiber-optic distribution links and within the panels by a microstrip phase-feed as illustrated on an earlier chart.

Subarray Assembly (324 Panels; 20, 736 Modules)

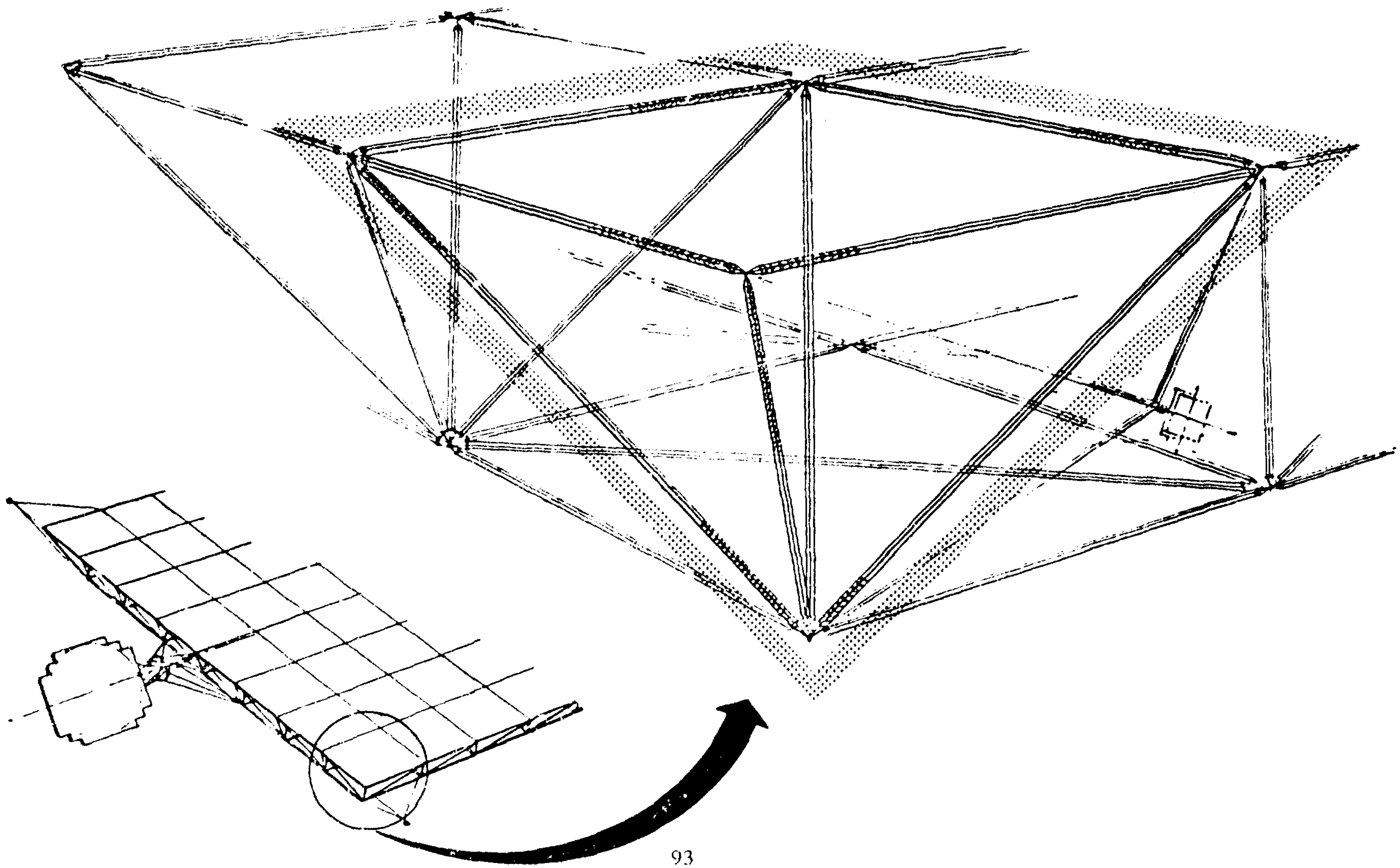


PRIMARY SOLID STATE SPS ARRAY STRUCTURE IS PENTAHEDRAL

Illustrated here is the pentahedral truss concept selected for the solid state SPS option. This represents an alternative to the reference hexahedral truss, providing about 10% mass savings.

Primary Solid-State SPS Array Structure is Pentahedral

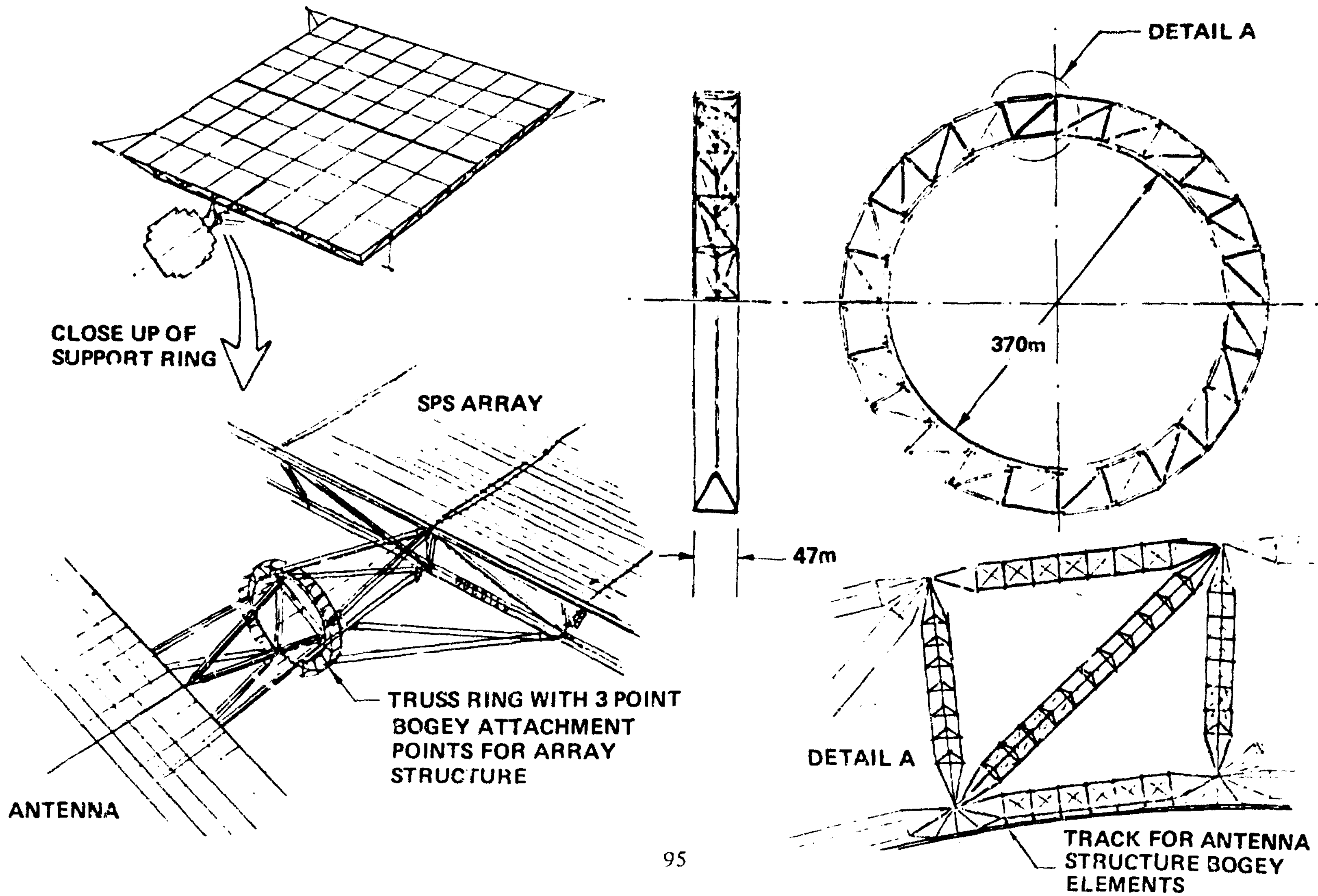
SPS-2966



ANTENNA SPS INTERFACE CONCEPT

The larger size of the solid state transmitter antenna has led to consideration of interface concepts that do not employ a yoke suspension. The concept illustrated here employs a truss tilt mechanism attached to the mechanical turntable rotary drive. Additional details are shown on the next chart.

Antenna – SPS Interface Concept

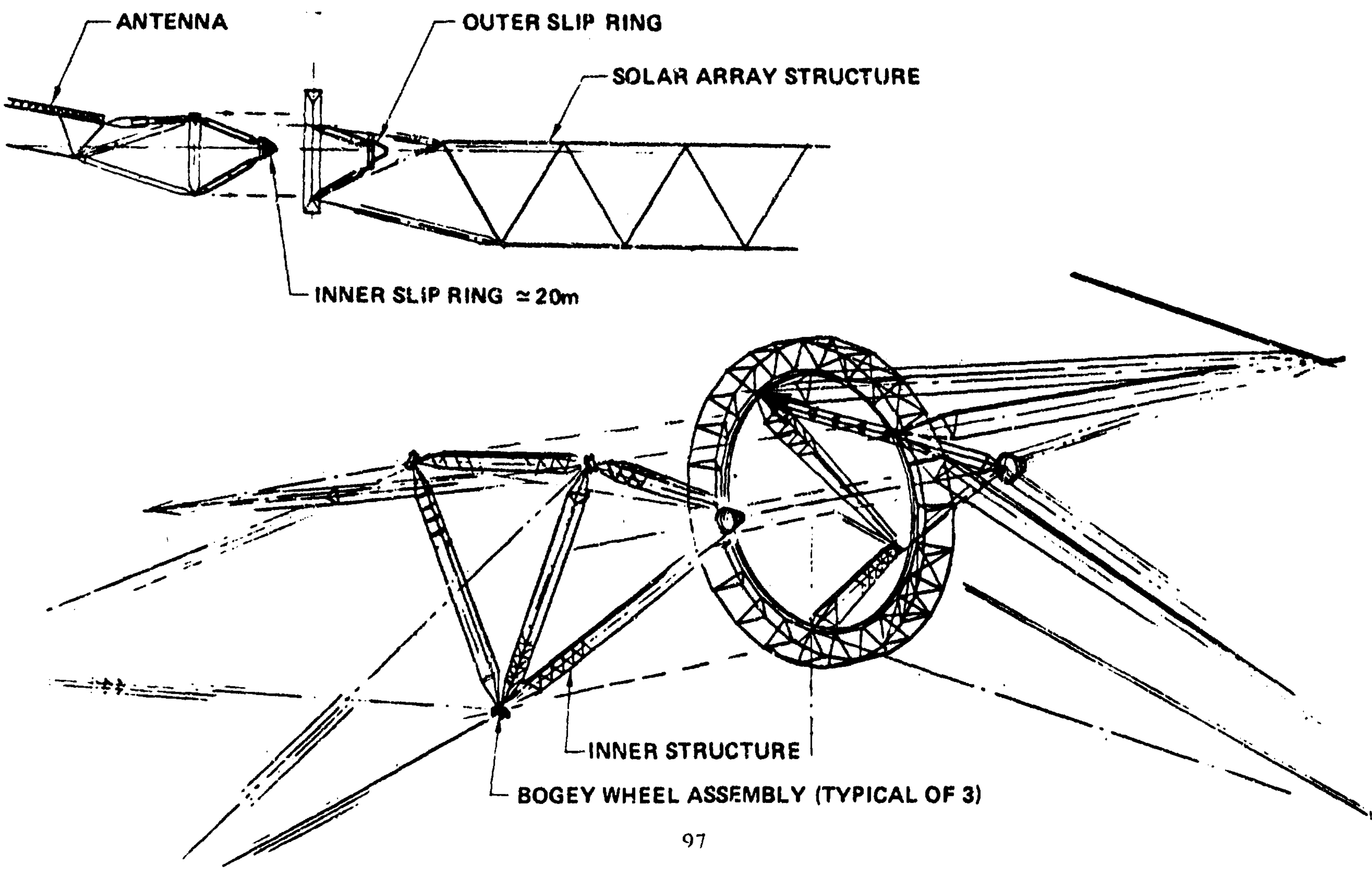


SLIP RING STRUCTURE WITHIN PRIMARY ROTARY JOINT

The relationships between the electrical slip ring structure and the mechanical rotary joint turntable drive are illustrated on this chart. The mechanical rotary joint employs a large bearing with three bogey wheel assemblies, a pyramidal truss structure and an end bearing that is co-located with the electrical rotary joint and slip ring assembly.

Slip Ring Structure Within Primary Rotary Joint

SPS-2984

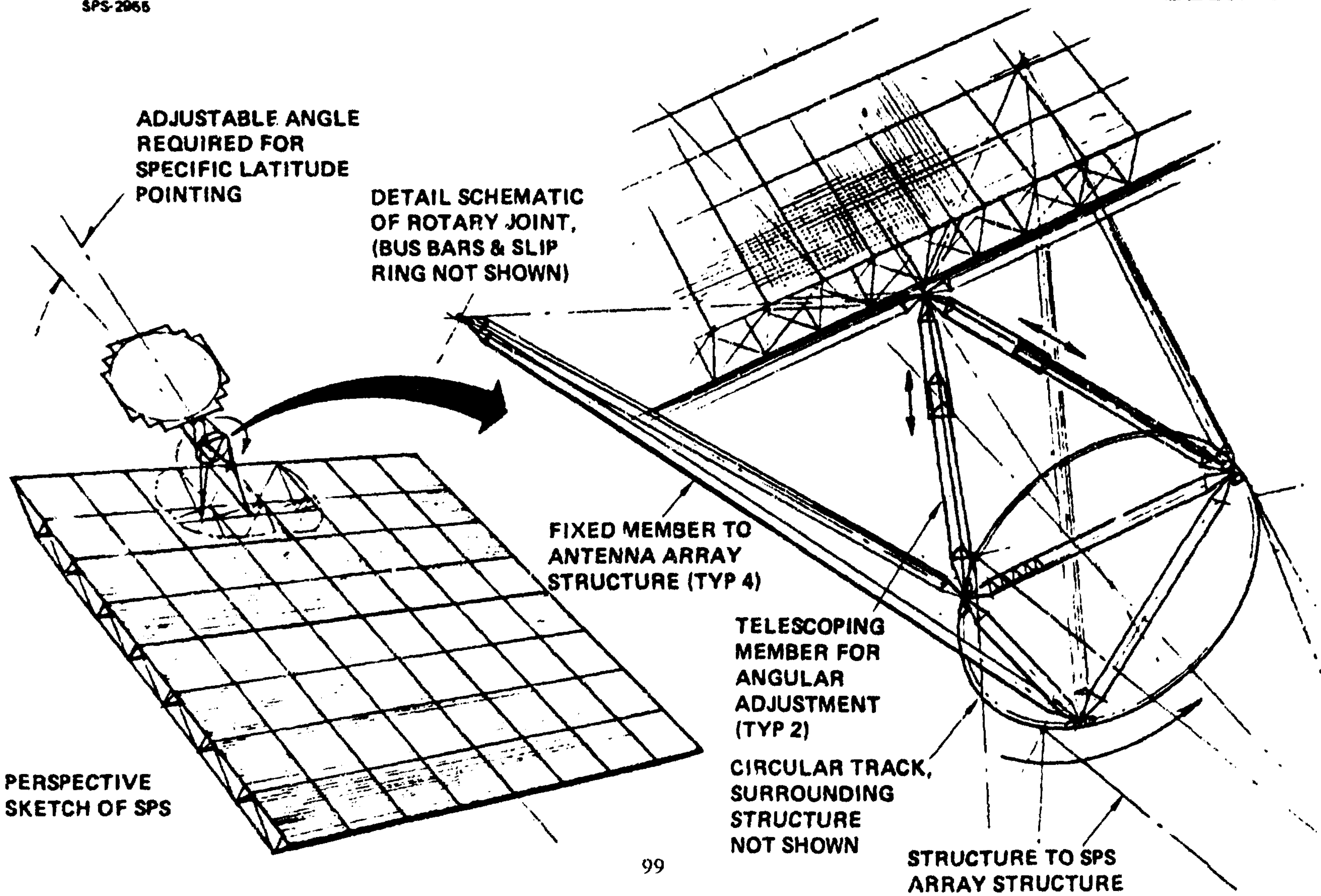


ANTENNA ARRAY ANGULAR ADJUSTMENT CONCEPT

Since large aperture antennas are needed for the solid state option, an investigation of alternative rotary joint assemblies was conducted. The concept shown here employs linear motor drives of the telescoping members, with electronic feedback, to establish the tilt angle for the transmitter necessary to accommodate the range of latitudes for the power beam. The electrical rotary joint would be similar to that shown on an earlier chart in the reference system description.

Antenna Array Angular Adjustment Concept
2.5 GW Solid-State SPS

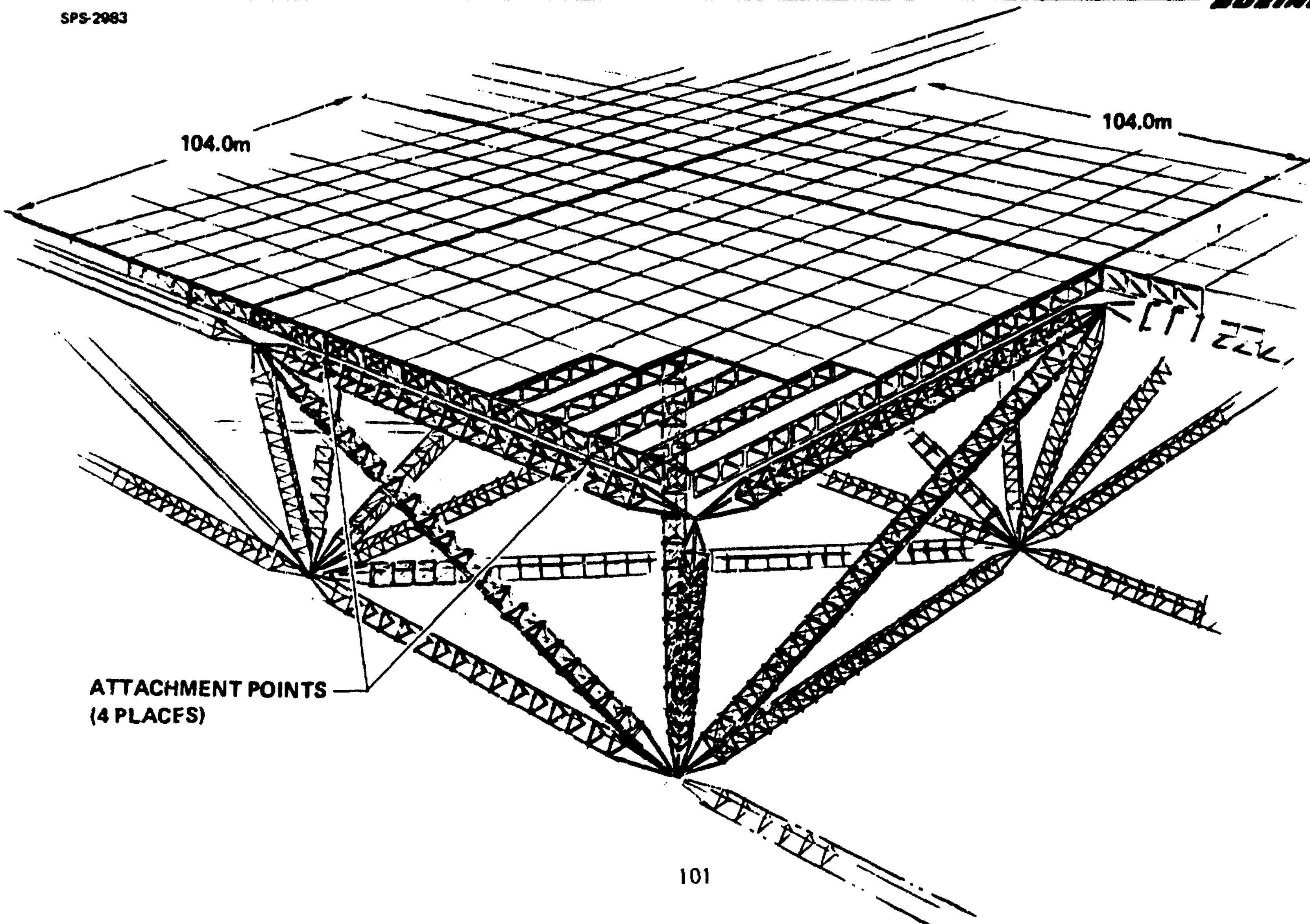
SPS-2966



THE ANTENNA SUBARRAY AND SUPPORT STRUCTURE INTERFACE

The support structure for the subarrays is comprised of simple linear truss members supported to the primary structure at four support points for each bay. This linear truss structure can be fabricated by beam machines or prefabricated and nested for shipment. This structural design approach provides a much simpler secondary structure than the earlier reference as well as improved access for maintenance equipment.

Antenna Subarray and Support Structure Interface



OPERATIONS

The operations summary includes the subjects indicated. Operations analyses are presented in more detail later in the briefing.

Operations

SPS-2939

- LAUNCH
- CARGO
- EARTH TO LEO
- LEO TO GEO
- MAINTENANCE

LAUNCH AND RECOVERY SITE SYSTEMS AND OPERATIONS

The tabulation facing summarizes the accomplishments of the launch and recovery site operations analysis.

Launch and Recovery Site Systems and Operations

- USED KSC AS REFERENCE LOCATION
- IDENTIFIED 14 HLLV AND PLV FACILITIES
  REFINED LOCATION OF THESE FACILITIES AT KSC
- REFINED THE CONFIGURATIONS FOR THE HLLV ORBITER AND PAYLOAD PROCESSING FACILITY AND THE HLLV BOOSTER PROCESSING FACILITY
- INTEGRATED THE HLLV LAUNCH PAD, HLLV ORBITER PROCESSING, AND HLLV BOOSTER PROCESSING TIMELINES
  - VERIFIED THAT 3 HLLV LAUNCH PADS ARE ADEQUATE
  - IDENTIFIED REQUIREMENT FOR 8 HLLV ORBITER AND 7 HLLV BOOSTERS (REDUCED FROM 10 AND 9 RESPECTIVELY)
- DEFINED COMMAND AND CONTROL FUNCTIONS AND INTERFACES
- UPDATED MANNING AND COST ESTIMATES

EARTH TO LEO TRANSPORTATION OPERATIONS ANALYSIS

The chart facing summarizes results of the earth-to-LEO transportation analysis.

Earth-To-Leo Transportation Operations Analysis

SPS-2942

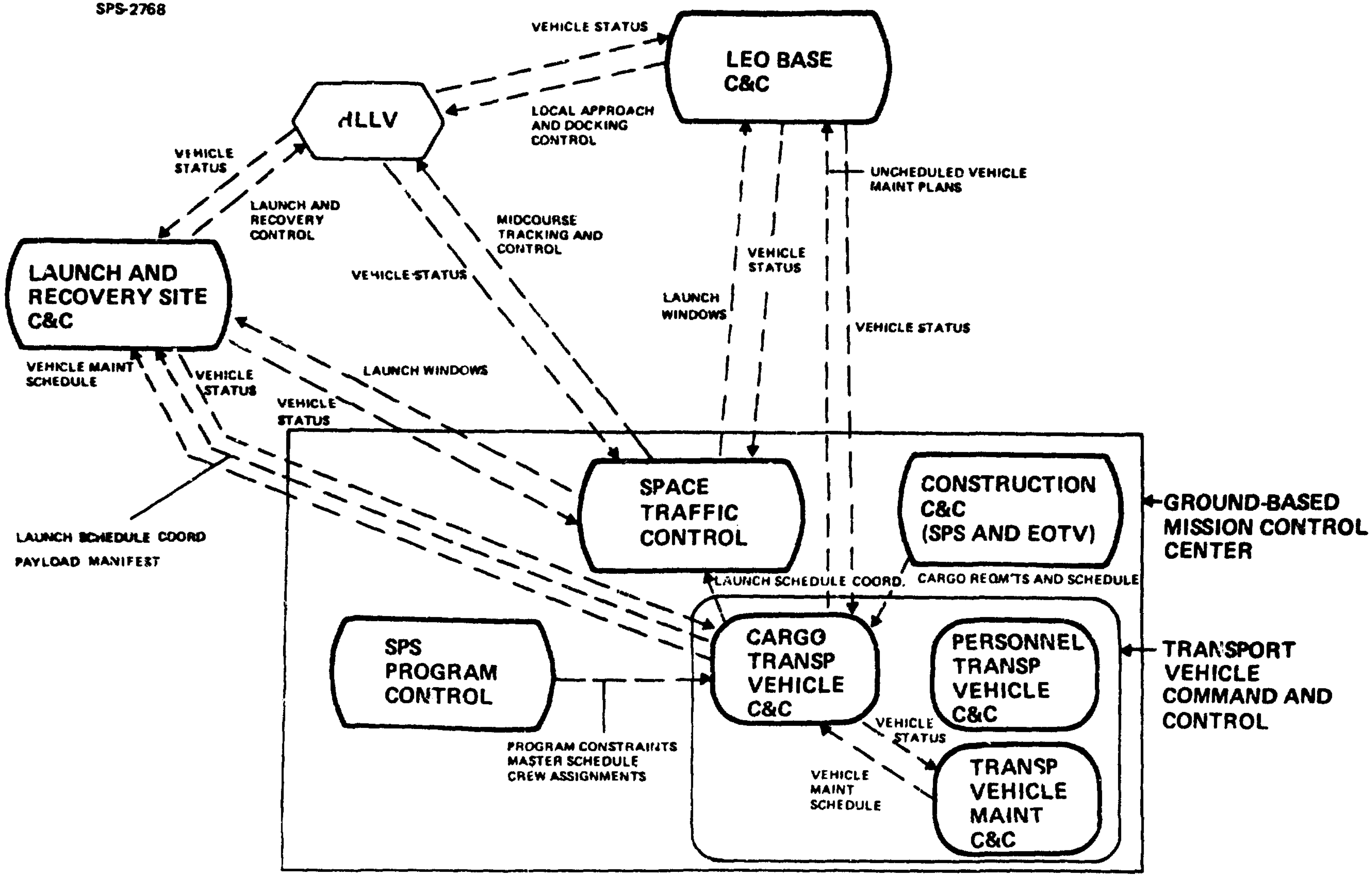
- DEFINED THE HLLV INTERFACE AT THE LEO BASE
  - DOCKING SYSTEMS AND OPERATIONS
  - PALLET HANDLING MACHINE
  - HLLV CREW TRANSFER SYSTEM
  - CARGO TRANSPORTERS
- DEFINED THE COMMAND AND CONTROL FUNCTIONS AND INTERFACES

EARTH TO LEO CARGO TRANSPORTATION COMMAND AND CONTROL

Command and control concepts were developed for all elements of the operations system. These are described in more detail in the operations analysis section of the briefing.

Earth-to-LEO Cargo Transportation Command and Control

SPS-2768



CARGO PACKAGING ANALYSIS

The facing chart summarizes results of the cargo packaging analysis.

Cargo Packaging Analysis

- IDENTIFIED CARGO PALLET FUNCTIONAL REQUIREMENTS
- IDENTIFIED COMPONENT RACK FUNCTIONAL REQUIREMENTS
- IDENTIFIED SHIPPING UNITS AND CONSUMPTION SCHEDULES FOR OVER 60 SPS AND EOTV COMPONENTS
- EVALUATED CONSUMPTION RATE SHIPPING SCHEDULE—FOUND TO BE INEFFICIENT
- EVALUATED SMALLER SIZE HLLV—(500,000 LB, 11x11x18M)
  - REQUIRES 60% MORE FLIGHTS
  - MANY OF THE "PRIMARY" COMPONENTS WOULD HAVE TO BE SUBSTANTIALLY REDESIGNED (SOLAR ARRAY, SUBARRAYS, CREW MODULES, THRUSTERS, ETC.)
- MASS-LIMITED PAYLOAD SETS IDENTIFIED
  - RECTANGULAR CARGO PALLET A MUST
  - 404 FLIGHTS/YEAR REQUIRED (THEORETICAL MINIMUM IS 372 FLIGHTS/YEAR)
- RECOMMEND THAT A COMPUTER GRAPHICS CARGO PACKAGING ANALYTICAL SOFTWARE BE CREATED

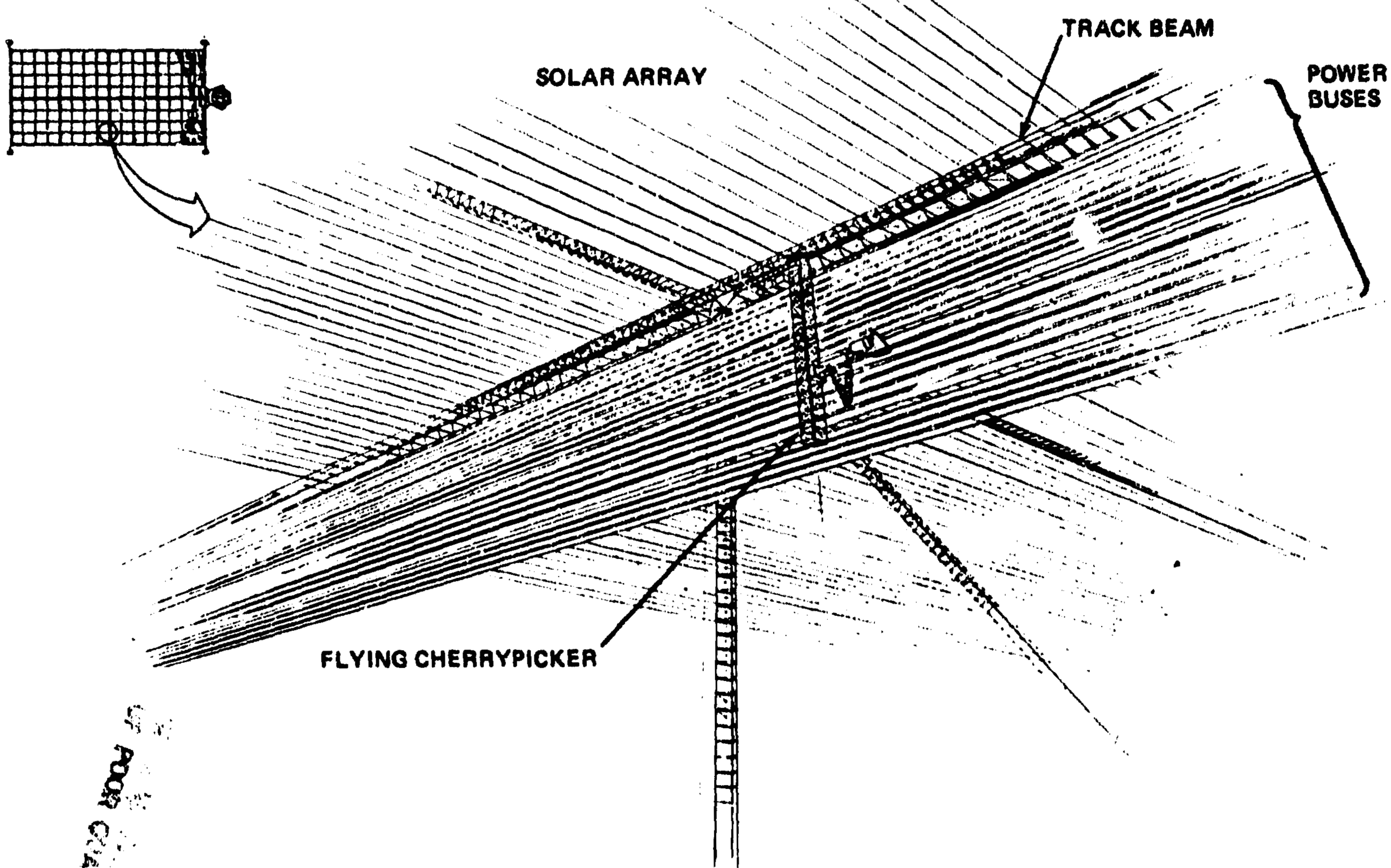
MAIN BUS MAINTENANCE ACCESS SYSTEM

The 1977 study examined maintenance of the klystrons on the power transmitter and did some comparisons of various means of flying and operating missions. During that study it was assumed that repair of components of the geosynchronous base would require the same size crew as the remove/replace operations at the satellites. During the present study further analysis was conducted on the maintenance systems in order to establish how maintenance access for all system components could be accomplished and to estimate actual crew counts both for remove/replace operations and for equipment repair operations at the geosynchronous base. Illustrated on this figure is a representative access concept for gaining access to power buses and switch gear. Additional definition of installation specifics was required in order to accomplish the maintenance analysis. Illustrated is the multiple bus power distribution system and a flying cherrypicker which is a part of the maintenance system.

D180-25402-1

Main Bus Maintenance Access System

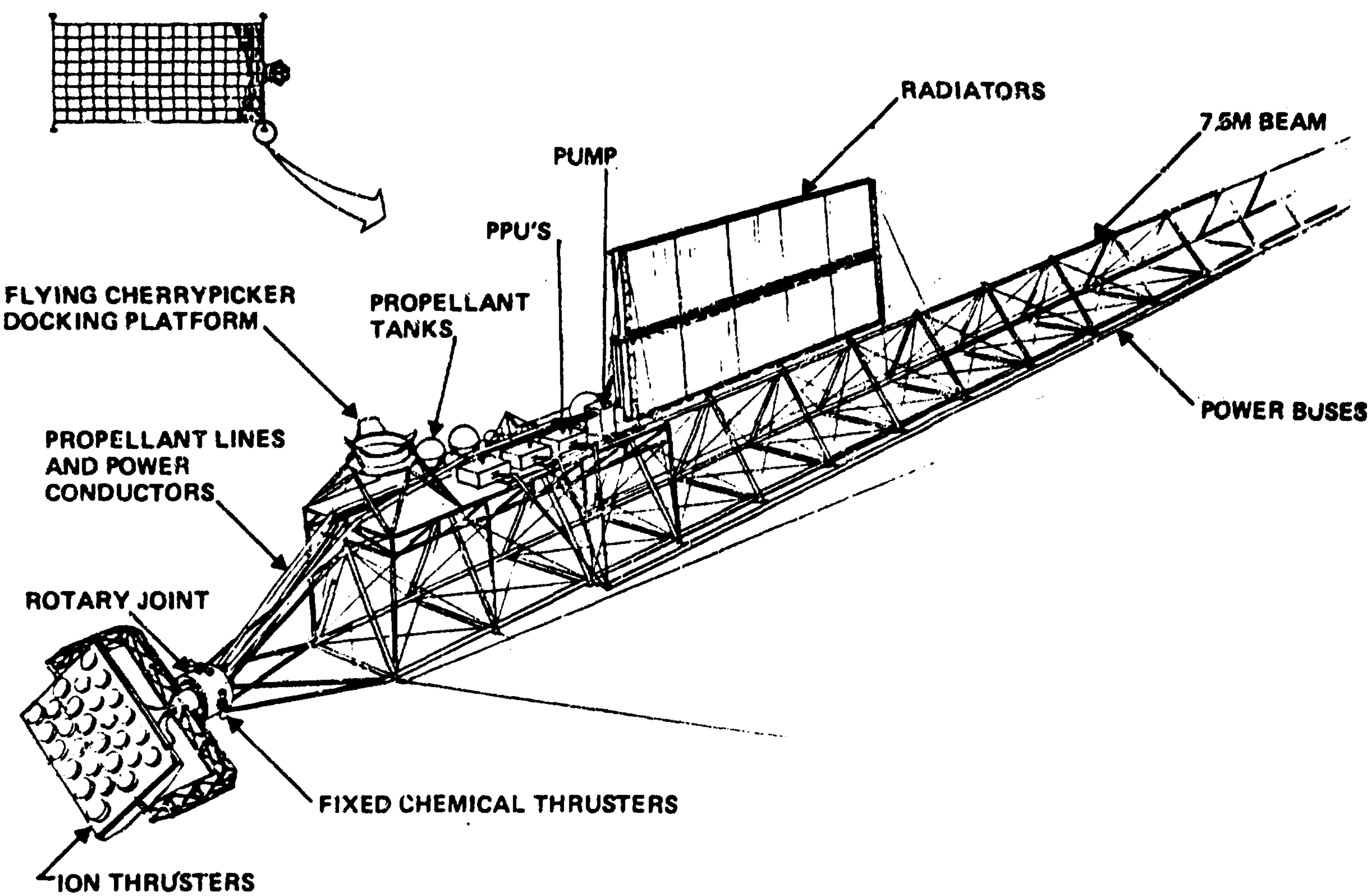
SPS-2699



SPS ATTITUDE CONTROL SYSTEM

The SPS attitude control propulsion system is illustrated on the facing page, showing maintenance provisions including the docking platform for a flying cherrypicker.

SPS Attitude Control System



MAINTENANCE ANALYSIS SUMMARY

The facing page summarizes the results of the maintenance and indicates the estimated cost of maintenance to be approximately 0.3 cent per kilowatt hour. This cost is categorized in utility language as operations and maintenance cost.

Maintenance Analysis Summary

- UPDATED EARLIER MAINTENANCE ANALYSIS
  - UPDATED FAILURE RATES
  - IDENTIFIED MAINTENANCE TASKS, DEFINED MAINTENANCE ACCESS SYSTEMS, TIMELINES, SPARES, CREW RQTS, & SUPPORT RQTS
- ASSUMED TWO 5,000-MEGAWATT SPS'S IN GEO
  - REMOVE/REPLACE CREWS 84
  - REPAIR CREW (AT GEO BASE): 350
  - SPARES ROUGHLY 800 MILLION DOLLARS/YEAR
  - ONE MOBILE MAINTENANCE SYSTEM; ONE MOBILE HABITAT; 4 OTV'S; 8 SPARES PALLETS; ONE FLYING CHERRYPICKER & OTHER EQUIPMENT
  - 3 ADDITIONAL HABITATES & 2 WORK MODULES AT GEO BASE
- ROM ANNUAL MAINTENANCE OPS COST

ITEM	OPERATING COST	SPARES COST	AMORTIZATION COST	TOTAL COST
CREW TRAN & OPS	$1220M			$1220M
SPARES		$800M		$ 800M
MAINT. SYS.	$ 200M	$100M	$250M	$ 550M

- COST/KWH = $\frac{\$2570M}{5 \times 10^6 \text{ KW} \times 8766 \text{ HRS} \times 0.9 \text{ PLANT FACTOR} \times 20 \text{ SPS'S}} = 0.32¢/\text{KWH}$

CURRENT SYSTEM ISSUES

The systems issues that are accorded principle importance today are those that will generally require experimental work to provide a sufficient database to develop conclusions or resolutions regarding those issues. Some of the principle issues are tabulated on the facing page.

Current Systems Issues

SPS-2832

- SOLAR CELL DEGRADATION, ENCAPSULATION, & ANNEALING
- SELECTION OF MICROWAVE TECHNOLOGIES
  - EFFICIENCY
  - NOISE
  - POWER SUPPLY
  - COST
  - CONFIGURATION ISSUES
- HIGH VOLTAGE, PLASMA, & CHARGING EFFECTS
- INTEGRATED STRUCTURE & CONTROL DYNAMICS
- HLLV SIZE & SHUTTLE/HLLV EVOLUTION
- PROTOTYPE/PILOT PLANT SIZE
- LASER TRANSMISSION

PLANS FOR BALANCE OF PHASE TWO

Tasks to be completed for the balance of Phase 2 are indicated on the facing page. Emphasis tasks will probably include additional microwave power transmission effort and improvement in traceability of the mass and cost data base.

Plans For Balance of Phase II

SPS-2988

- COMPLETE DEFINITION OF SOLID STATE REFERENCE SPS
  - DC/AC POWER DISTRIBUTION TRADEOFF
  - PHASE CONTROL NETWORK
  - MASS AND COST ESTIMATES
- DEVELOP INTEGRATED OPERATION DESCRIPTION
- UPDATE REFERENCE SYSTEM DESCRIPTION
- EMPHASIS TASKS TO BE DETERMINED
- DOCUMENTATION

SPS MICROWAVE POWER TRANSMISSION SYSTEM MID-TERM REVIEW

This section of the briefing presents the report on Phase II work accomplished on microwave power transmission systems, anaylsis and definition.

SPS

MICROWAVE POWER TRANSMISSION SYSTEM

MIDTERM REVIEW

MTPS STUDIES

The briefing is presented in three principal segments: discussion of the solid-state power combiner radiator module, a section on pattern studies and a section on phase control flight test concepts.

BOEING SOLID STATE SPACETENNA A REVIEW AND UPDATE

The solid state spacetenna design activity was initiated on IR&D in 1978. A concept for a transmitting antenna module developed initially for another purpose was modified and adapted to combine power from several solid state power amplifers into a single double-slot radiator module. During Phase II of the present study, additional work has been conducted to embody this design concept into a solid state SPS transmitter design. The review and update reported here includes IR&D results on the basic design principle of the solid state power combiner.

MPTS STUDIES

	CONTRIBUTORS
o SOLID STATE MODULE	GEORGE FITZSIMMONS
o PATTERN STUDIES	SCOTT RATHJEN RAY SPERBER
o PHASE CONTROL FLIGHT TESTS CONCEPTS	WALT LUND RICH REINERT RAY SPERBER

BOEING SOLID-STATE SPACETENNA

A REVIEW & UPDATE

BOEING SOLID STATE SPACETENNA SUMMARY OF EFFORT

Basically four aspects of solid state spacetenna have been addressed. These are (1)low-loss power-combining antenna module, (2)the electronics in that module including closed-loop RF amplifers, (3)integration of the module into a panel useful for further integration into subarrays to make up a solid state spacetenna, and (4)reliability analysis of the modules both by themselves and when in the presently-conceived solid state spacetenna configuration.

On low-loss power combining, a four-way combining antenna has been constructed and demonstrated. An improved version of this has been proposed featuring reduced cross-polarization loss, wider band width and a physically smaller antenna to allow higher RF power per unit area across the spacetenna face.

Solid state module electronics design has resulted in a configuration of four five-watt RF amplifiers per module which would provide a 20-watt RF output from the module, .4 x .7 wavelengths in area. The amplifiers would have 43 dB nominal gain and would be phase-error-corrected for phase shifts in the amplifier chain. This is to be done by sampling the module output, and feeding it back to phase shifters which would correct it to be appropriately in-phase with the input. An electronics design study verified that the module size of .4 x .7 wavelengths was close to the minimum achievable with our configuration.

64 modules may be integrated in an 8x8 configuration into a panel that is also the smallest line replacable mechanical unit. A single RF feed per panel is envisioned. The same thing is true for the DC feed, however, the modules are hooked in a series parallel configuration.

Reliability analysis of the modules concentrated on string reliabilility which was found to be the key factor in the reliability of this configuration. In addition, electronics to protect against the effects of open-circuited modules was designed.

BOEING SOLID-STATE SPACETENNA

Summary of Effort

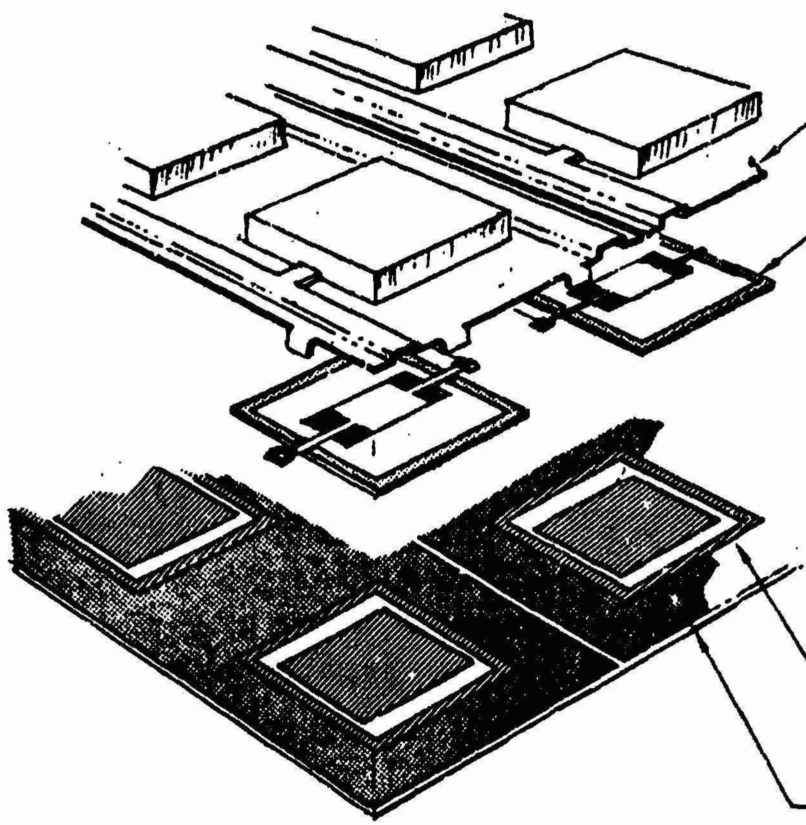
- **LOW-LOSS POWER COMBINING ANTENNA**
  - Demonstrated 4 way combining antenna
  - Improved 4 way combining antenna proposed
    - * Reduced cross polarization loss
    - * Width bandwidth
    - * Smaller antenna for improved power density
- **MODULE ELECTRONICS WITH CLOSED LOOP RF AMPLIFIERS**
  - 20 watts out, 43 db gain with closed loop phase error correction. (80 watts/λ^2)
  - Electronics design study to verify module size (.4λ x .7λ minimum)
- **INTEGRATION OF MODULE INTO USABLE PANEL**
  - RF feed (64 element panel)
  - DC feed (series parallel)
- **RELIABILITY**
  - String reliability analysis
  - Module open circuit protection

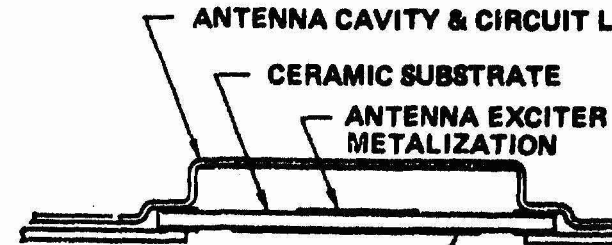
SOLID STATE ANTENNA EXPLODED DIAGRAM

The basic configuration of the solid state modules in the antenna is shown. The core of the module is a sheet of ceramic substrate on which microstrip circuitry is metalized. An aluminum carrier underneath the substrate and an aluminum back cover fully enclose the electronically active circuitry on the substrate. Power amplifier integrated circuits would be mounted in holes in the substrate directly on the aluminum carrier to provide a good thermal path for heat rejection.

Microstrip Slotline Radiator Concept

(active modules, DC & RF feed lines not shown)





SOLID STATE MODULE ANTENNA PATTERN

The antenna pattern along an E-plane cut of a solid state module excited with a single feed has been measured. The on-axis gain was found to be 5dB over isotropic.

THE BOEING COMPANY

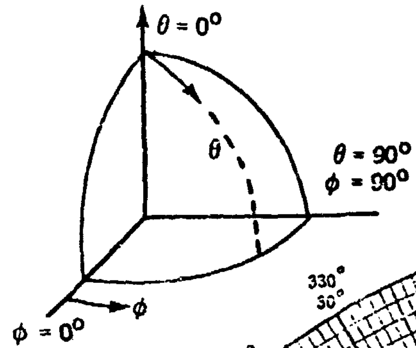
DATE 12-12-78 SHEET ____ OF ____

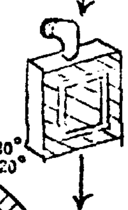
VEHICLE TYPE ____ MODEL SCALE ____

ANTENNA TYPE MICROSTRIP (SINGLE FEED)

ANTENNA LOCATION COPPER GROUND PLANE

FULL SCALE FREQUENCY 2.45





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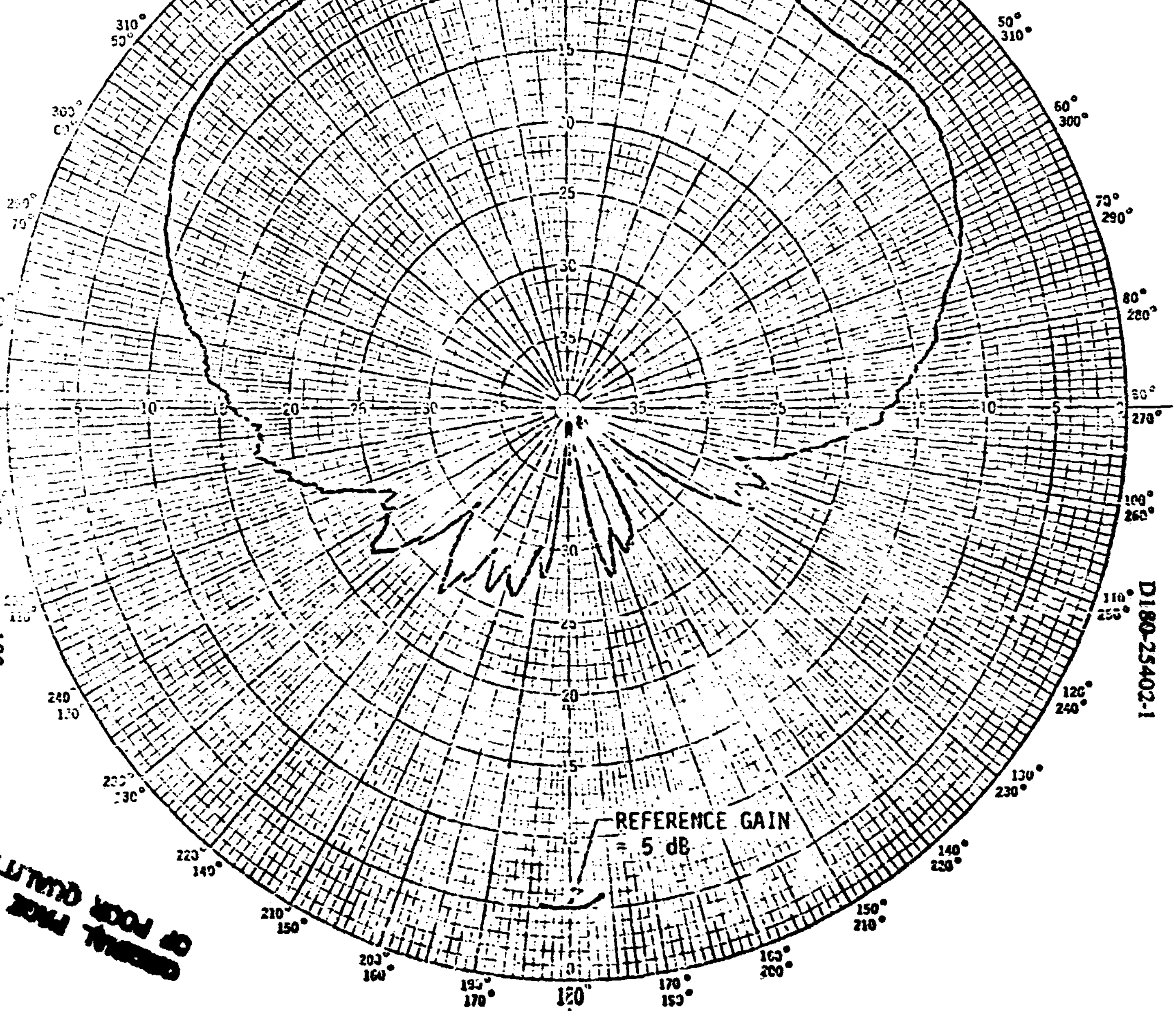


ORIGINAL PAGE IS OF POOR QUALITY

REMARKS ____

VARIABLE ANGLE ϕ ( ), θ ( )

CONSTANT ANGLE ϕ = ____ θ = ____

POLARIZATION E_ϕ ( ), E_θ ( ). ____

CURVE PLOTTED IN DECIBLES ____

ENGINEER ____

RANGE ____

Polar Chart No. 1270
SCIENTIFIC-ATLANTA, INC.
ATLANTA, GEORGIA

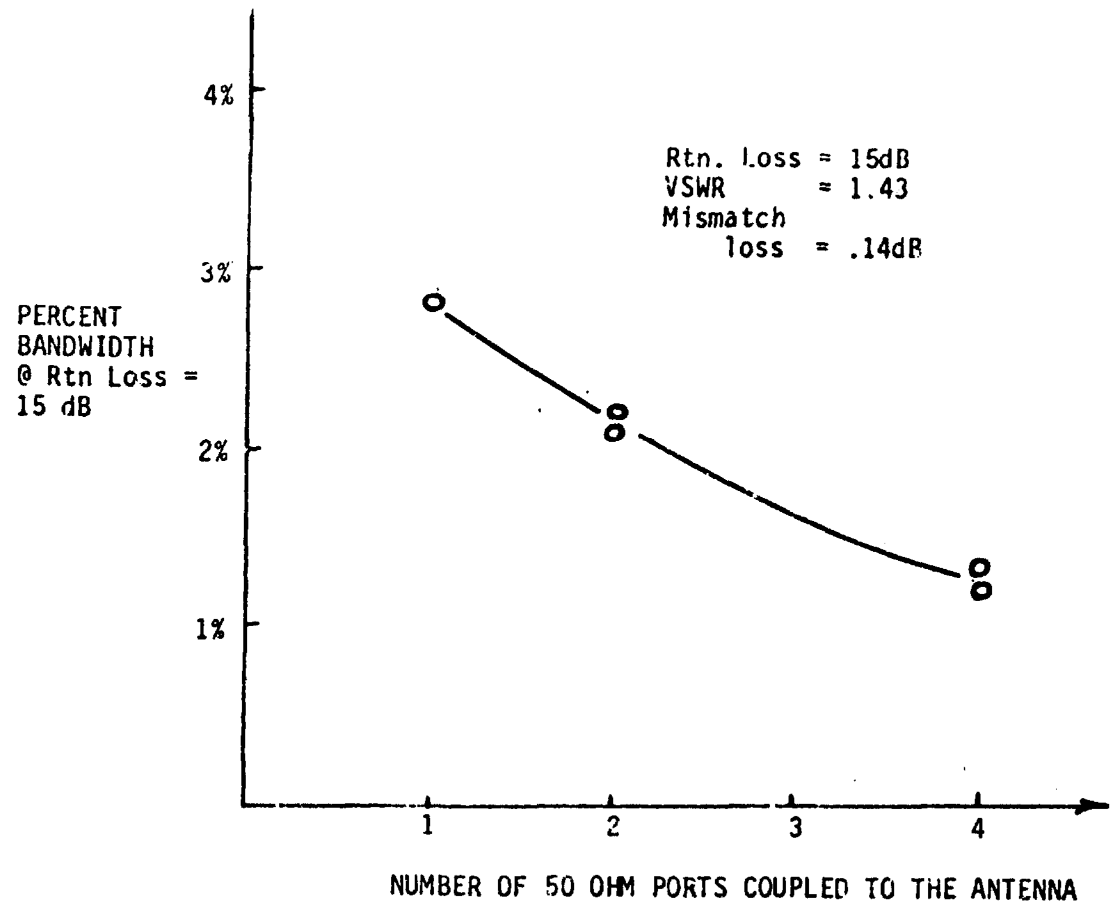
X 21801 REV 4/78

315-024

POWER COMBINING ANTENNA BANDWIDTH VERSUS NUMBER OF PORTS

The bandwidth of the solid state antenna module depends on the number of exciters inside the module cavity. This has been experimentally measured. The bandwidth has been found to go roughly as the inverse square root of the number of ports with 3% bandwidth at one port.

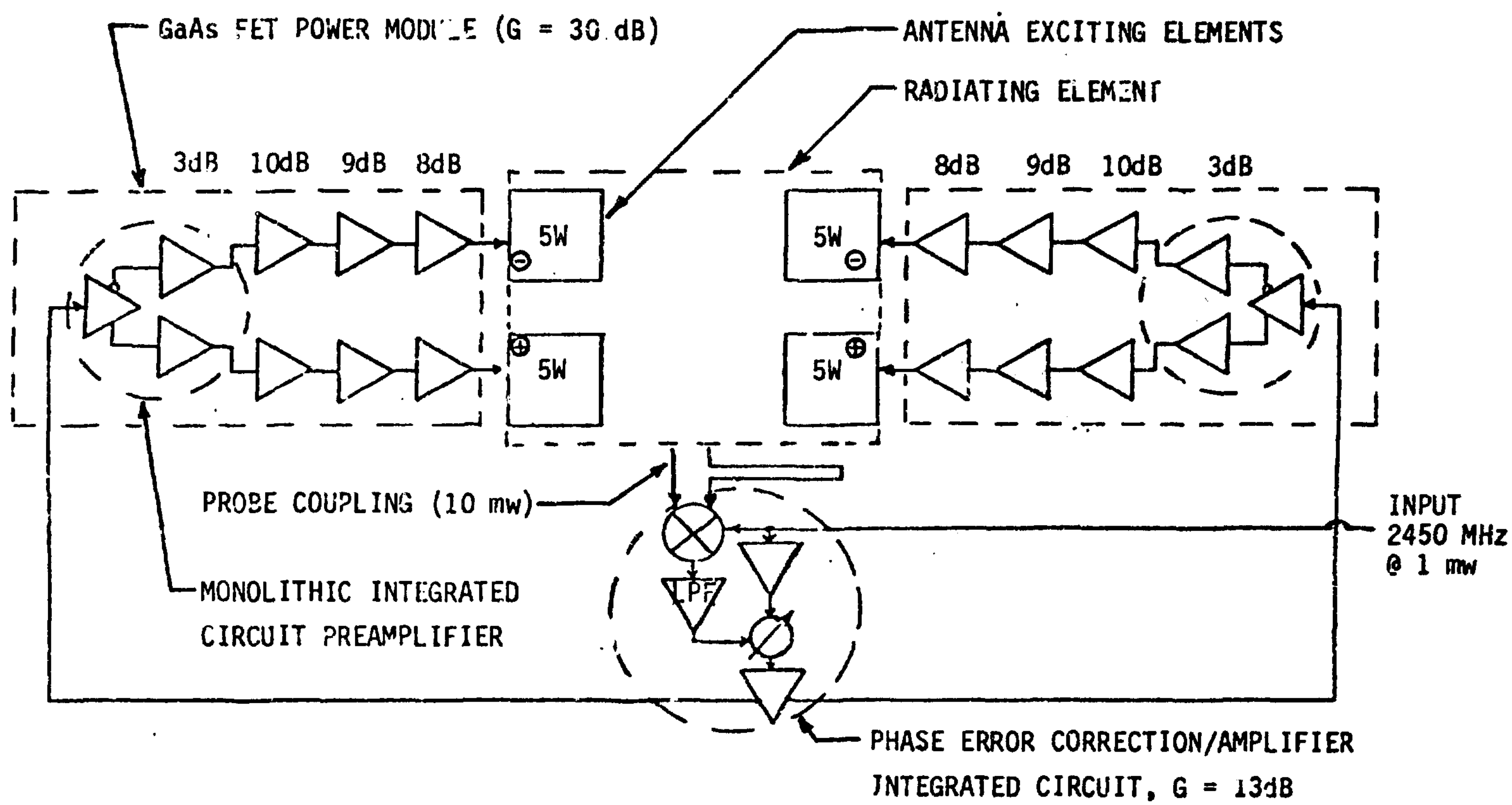
POWER COMBINING ANTENNA BANDWIDTH VS NUMBER OF PORTS



SOLID STATE POWER MODULE BLOCK DIAGRAM (20 WATTS)

A block diagram of the currently-preferred four-exciter solid state module is shown. The input signal to the module is used as a phase reference for comparison with the probe-coupled module output to provide phase error correction for module amplifier through-phase variations. This should greatly enhance the module phase stability with respect to aging and temperature variations.

SOLID-STATE POWER MODULE BLOCK DIAGRAM (20 WATTS)



LOW COST - LOW MASS SOLID STATE SPACETENNA CONCEPT

A 64-module panel design was developed. The modules consist of 5 basic components. These are the power amplifier subassembly, of which each module has two, a drive and phase error correction subassembly (one per module), a ceramic substrate (one per module), and a two-piece aluminum frame and back cover assembly.

This concept has a number of special attractive features. First is the ability to combine microwave power from a number of amplifiers with low loss. Secondly, it corrects for phase errors in the module amplifier chain. Also, all the electronics are packaged into two subassemlies. This simplifies radiation shielding, (which may be integral), pretesting, burn-in and should provide a sufficiently high volume of demand for common parts so that getting multiple suppliers for them is no problem. The high thermal conductivities of the ceramic substrates and aluminum stampings in the waste heat rejection path allow radiation of that heat at the maximum possible temperature. Series-paralleling the modules allows a single-voltage antenna panel with integral DC conduits. All external module surfaces are at local module ground and circuitry protects against open-circuited modules. The modules have visual indication of failure which eases the workload of fault isolation.

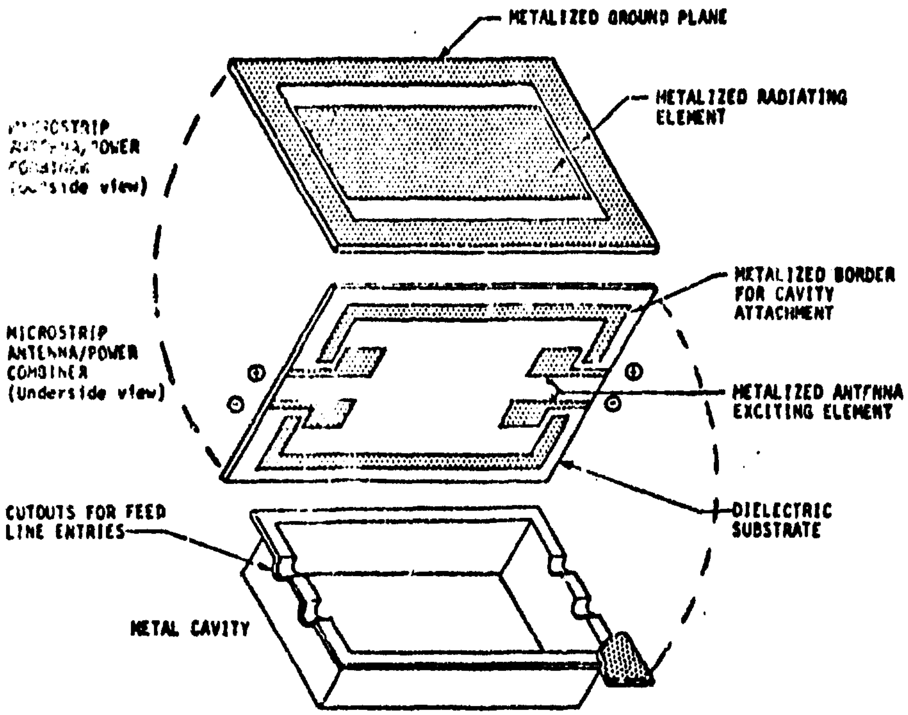
LOW COST, LOW MASS SOLID-STATE SPACETENNA CONCEPT

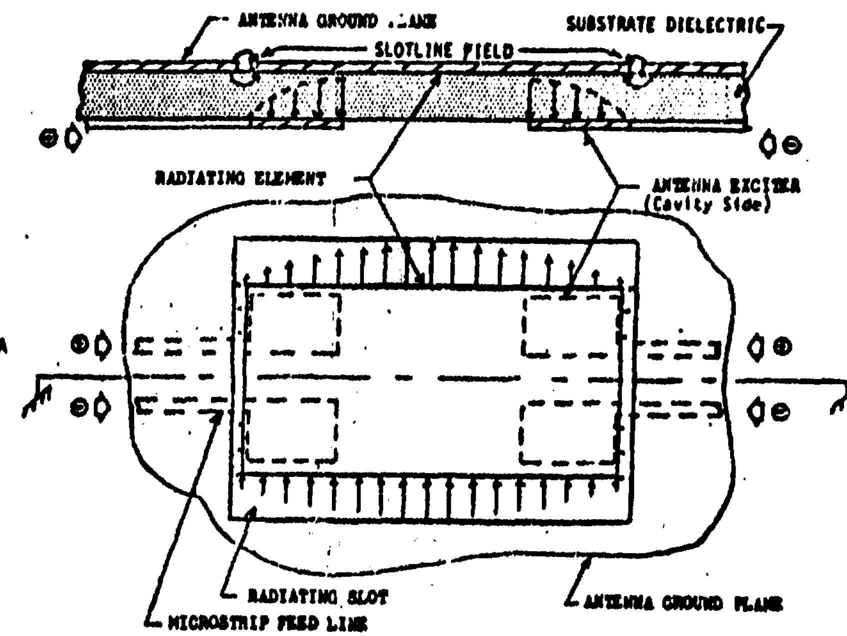
- SIMPLE 3 COMPONENT SOLID-STATE PANEL (64 MODULES)
  - Power amplifier subassembly (2 each/module)
  - Drive and phase error correction subassembly (1 each/module)
  - Ceramic antenna substrate (1 each/module)
  - Two piece aluminum frame
- SPECIAL ATTRACTIVE FEATURES
  - Low loss power combining antenna
  - Closed loop RF module for phase stability
  - All electronics packaged into two subassemblies
    - integral radiation shielding
    - enables pretesting and burned-in
    - multiple suppliers
  - High thermal conductivity system to radiate waste heat
    - aluminum stampings
    - ceramic substrates
  - Single voltage system suitable for series parallel
    - antenna doubles as a dc conduit
    - all external surfaces at ground potential
    - open circuit module protection circuitry
    - fault isolation

POWER COMBINING MICROSTRIP ANTENNA

An exploded view and field patterns for the currently preferred solid state module are shown. Note the relatively small area of the exciter pads in the cavity.

POWER COMBINING MICROSTRIP ANTENNA





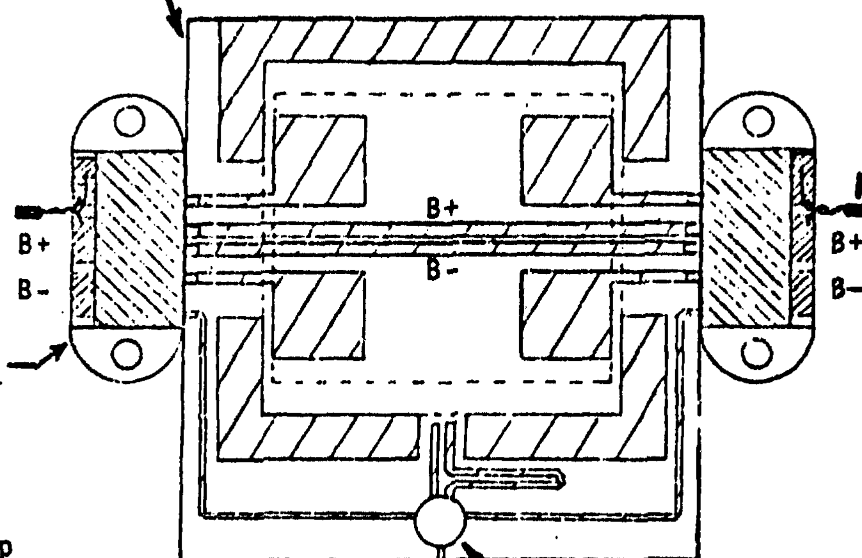
SOLID STATE POWER MODULE CONCEPT (20 WATTS)

Top view of the layout of the circuitry in solid state module is shown. Power supply lines may be fed through the zero field node at the center of the module from one hybrid GaAs FET power module to the other to simplify power supply line routing.

SOLID-STATE POWER MODULE CONCEPT (20 WATTS)

RADIATING ELEMENT POWER COMBINING
- Antenna exciters (4)
- Low loss combining
- Ceramic substrate
- Metalized both sides (thick film)

FAIL SAFE FEATURES
- Open circuit protection
- Heat radiated to space



GaAs FET POWER MODULE
- 30 dB gain
- 10 watts output
- Hybrid technology
- Sapphire, microstrip

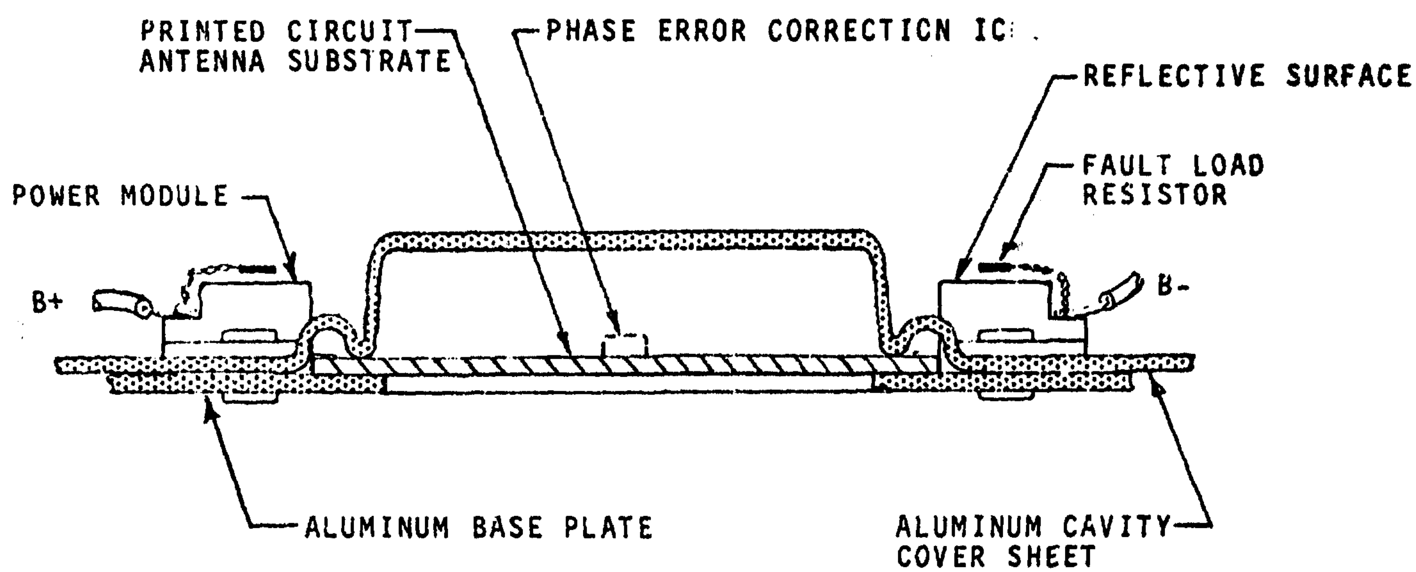
PHASE ERROR CORRECTION
- Printed cavity coupling probes
- Single GaAs chip integrated circuit
  - Phase detector
  - Low pass filter
  - Phase shifter
  - 2450 MHz amplifier

INPUT (2450 MHz @ 1 mw)

SOLID STATE POWER MODULE CROSS-SECTION

A cross sectional view of the solid state power module illustrates the relative locations of the components in the module. Note the nichrome fault load resistor mounted above the hybrid power modules which will dissipate the module power in case the power amplifier circuitry opens. Upon failure of the hybrid power module circuitry, the fault load resistor will be switched in to dissipate the power and will glow rejecting heat at high temperature and providing a visual indication of failure.

SOLID-STATE POWER MODULE CROSS SECTION



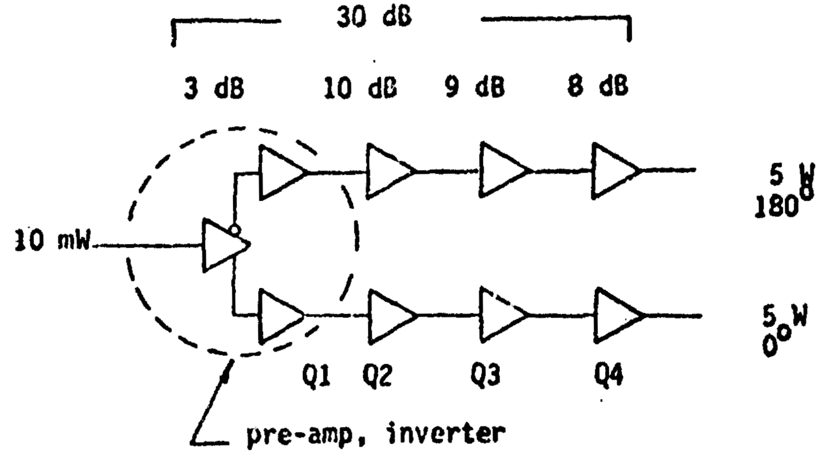
2.45 GHz POWER AMPLIFIER MODULE

- 30 DB GAIN, 2-5W OUTPUTS, 180° PHASE DIFFERENCE; DC OPEN CIRCUIT PROTECTED
- SINGLE VOLTAGE SUPPLY
- MODULE CASE IS INSULATED FROM ALUMINUM FRAME
- HYBRID INTEGRATED CIRCUIT
    - .010" SAPPHIRE SUBSTRATE WITH PRINTED INDUCTORS, RESISTORS, AND CAPACITORS.
    - GAAS PREAMP-INVERTER MONOLITHIC INTEGRATED CIRCUIT CHIP
    - DISCRETE GAAS FET POWER AMPLIFIER CHIPS
    - MODULE BIAS DERIVED BY RECTIFICATION OF OUTPUT RF OR BY SELF BIAS.
    - FAIL-SAFE INTEGRATED CIRCUIT CHIP

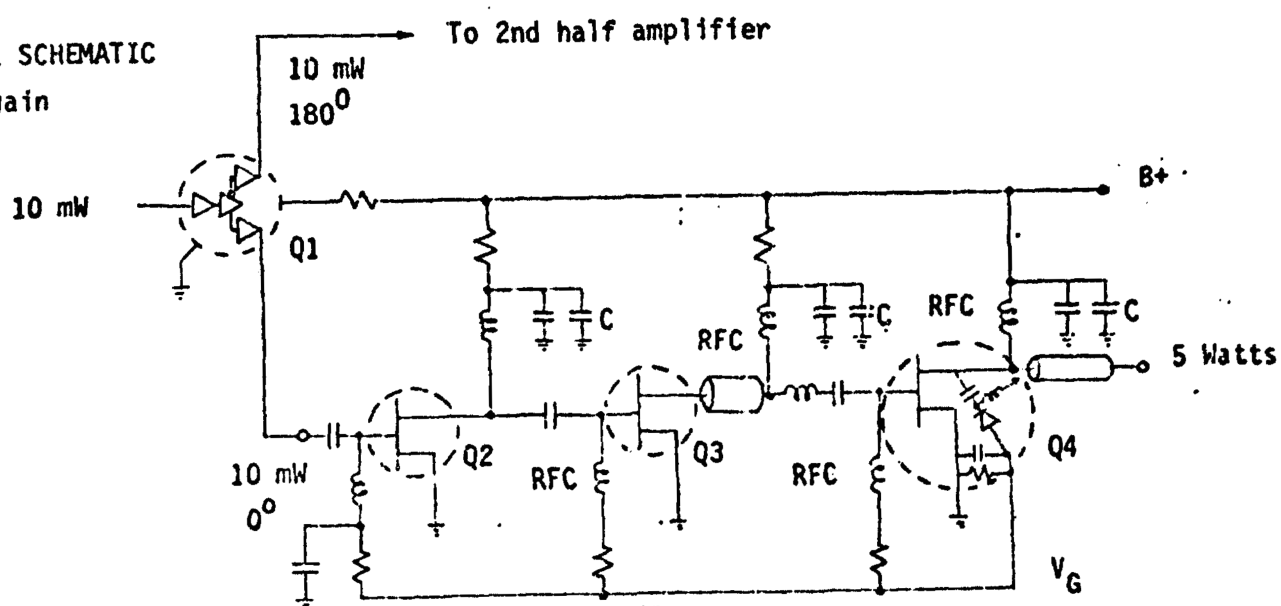
2.54 GHZ POWER AMPLIFIER MODULE

PRELIMINARY

A. BLOCK DIAGRAM



B. TYPICAL SCHEMATIC
30 dB gain



PRELIMINARY 2.54 GHz POWER MODULE LAYOUT

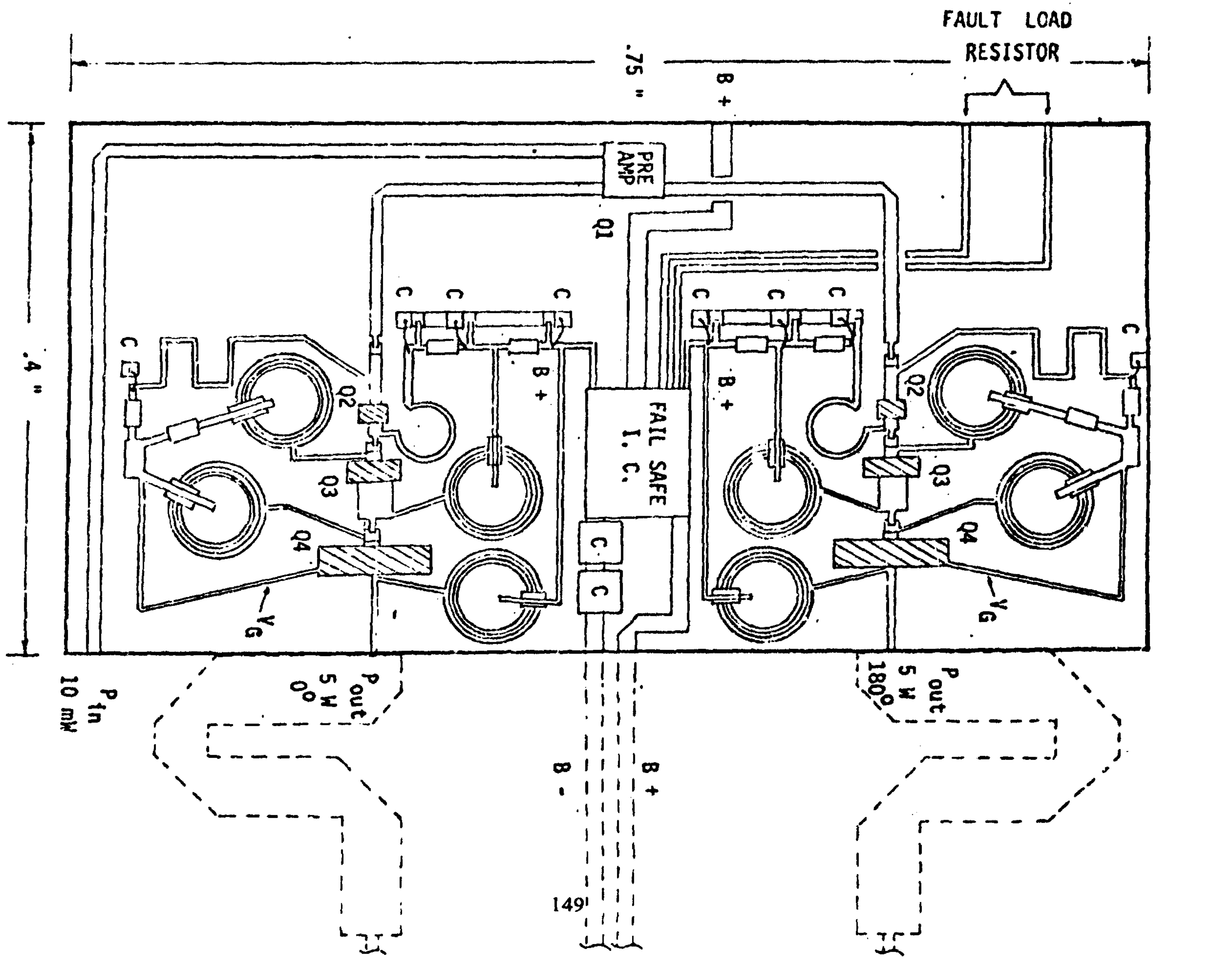
Hybrid technology circuitry for the power amplifier modules has been laid out and is shown. The physical size is somewhat larger than desired. It may be possible to reduce this.

BOEING MICROWAVE CIRCUITS

D180-25402-1

2.45 GHz POWER MODULE LAYOUT

PRELIMINARY



MODULE PHASE ERROR CORRECTION

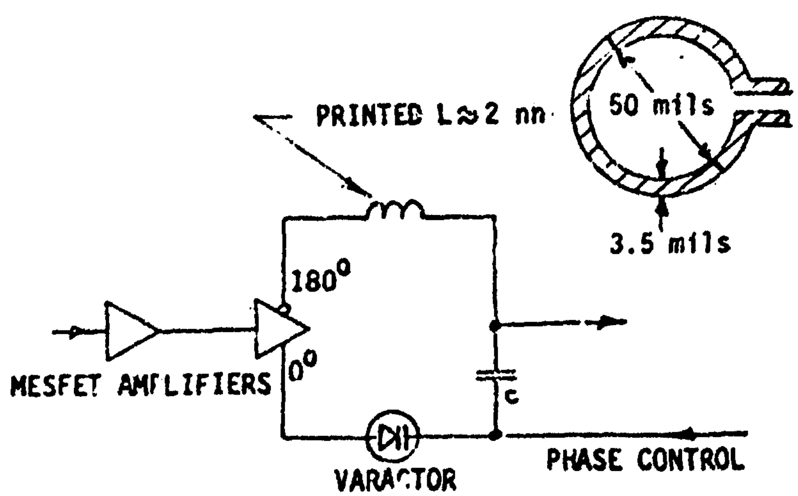
Features of the module phase error correction circuitry are the low parts count, automatic constant phase error difference between input and output, lack of intervening signal conditionings circuitry and two separate outputs for driving separate power modules.

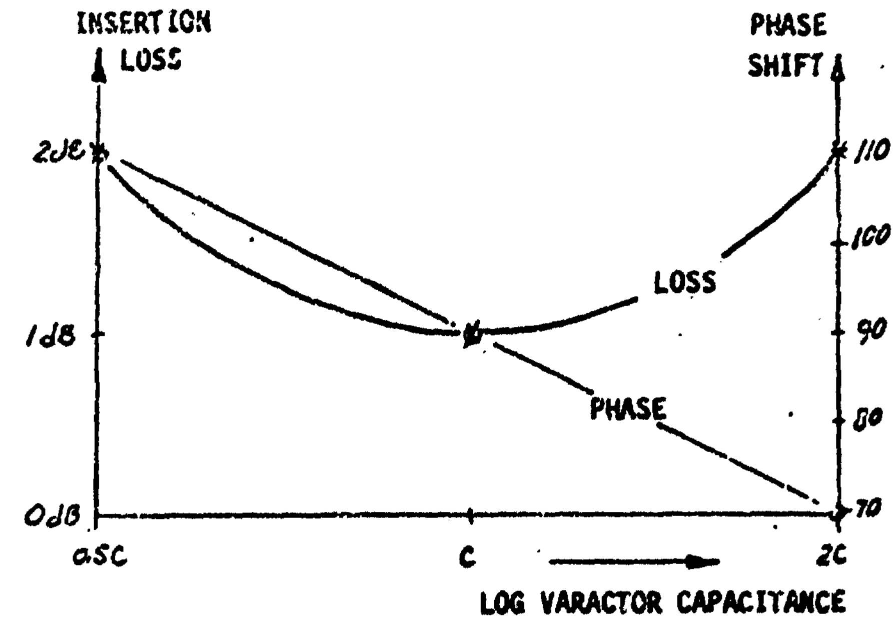
MODULE PHASE ERROR CORRECTION

- SINGLE INTEGRATED CIRCUIT, TWO CHIP CAPACITORS, ONE PRINTED CAPACITOR, AND ONE PRINTED INDUCTOR.
- AUTOMATICALLY HOLDS A CONSTANT PHASE DIFFERENCE BETWEEN THE RF INPUT AND THE RADIATED RF POWER.
- THE RF INPUT AND THE SAMPLED OUTPUT POWER ARE PHASE COMPARED WITH NO INTERVENING SIGNAL CONDITIONING WHICH WOULD CONTRIBUTE ERRORS.
- PROVIDES TWO OUTPUTS FOR DRIVING SEPARATE POWER MODULES.

PHASE SHIFTER

The ba c phase shifter circuit is shown along with phase shifter insertion loss and phase shift as a function of the log of the varactor capacitance.


PRINTED L ≈ 2 nh
50 mils
3.5 mils
180°
0°
MESFET AMPLIFIERS
C
VARACTOR
PHASE CONTROL

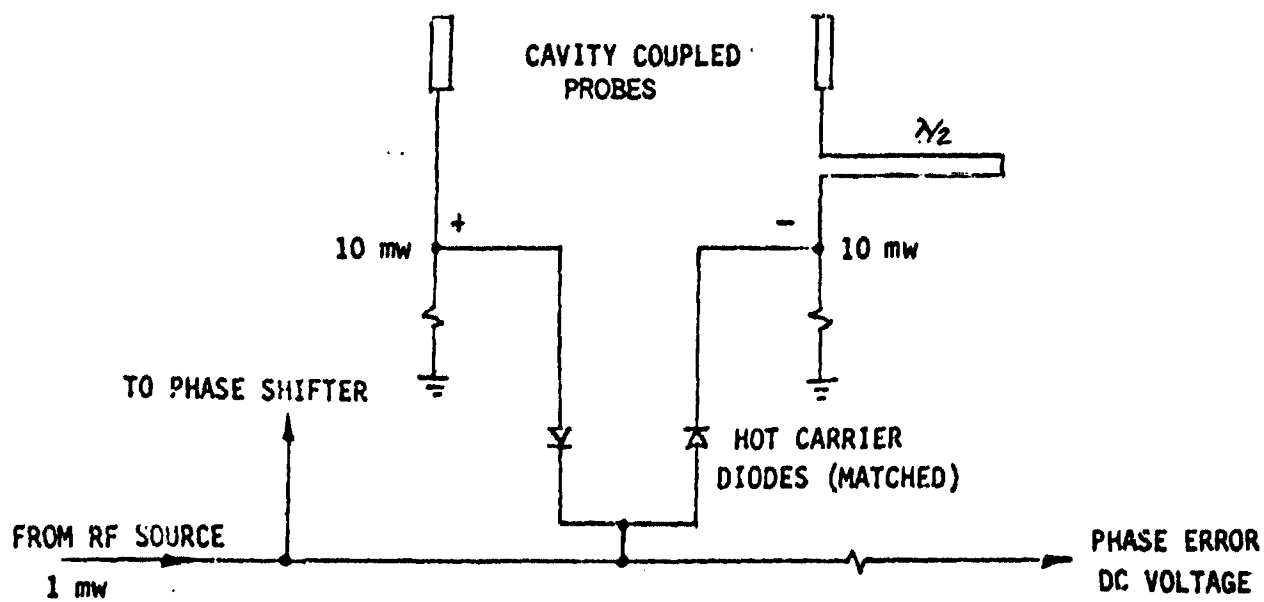

INSERTION LOSS
PHASE SHIFT
2dB
1dB
0dB
110
100
90
80
70
LOSS
PHASE
.5C
C
2C
LOG VARACTOR CAPACITANCE

PHASE DETECTOR

Two probes in the cavity pick up the module output signal this is then halfwave rectified by two hot-carrier diodes to become the phase error DC voltage which is superposed on the one milliwatt RF input to the module.

PHASE DETECTOR

PRELIMINARY

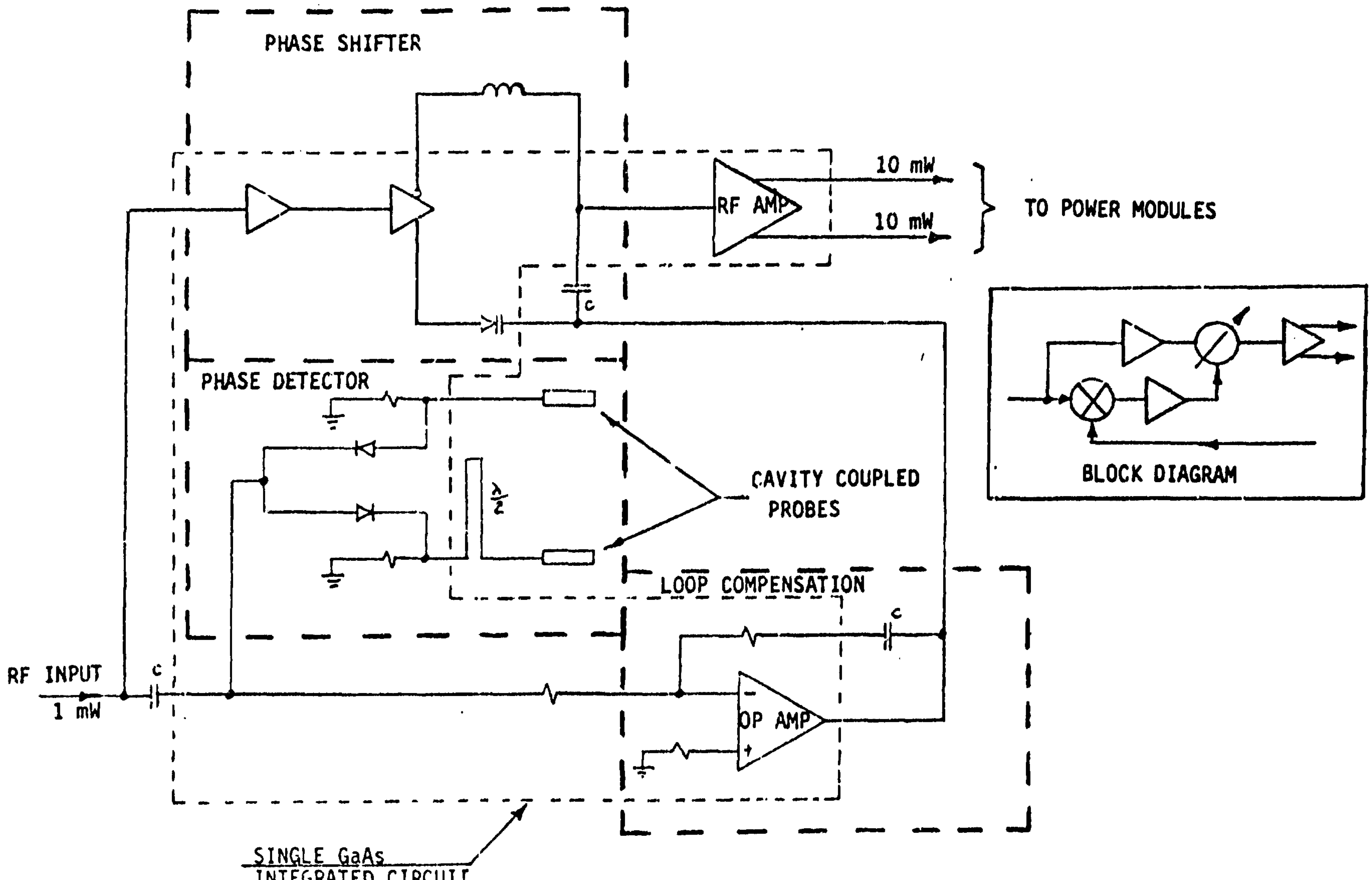


MODULE PHASE ERROR CORRECTION

The phase shifters, phase detectors and amplifiers are combined to become the complete module phase error correction circuitry, shown here.

MODULE PHASE ERROR CORRECTION

PRELIMINARY



POWER MODULE FAIL SAFE CIRCUITRY

- "OPEN" FAILURE TRIGGERS THE SCR WHICH SUBSTITUTES A METALLIC FAULT RESISTOR AS A LOAD AND MAINTAINS THE MODULE VOLTAGE.

- ANY NUMBER OF MODULES MAY FAIL "OPEN" WITHOUT DISTURBING THE OTHERS.

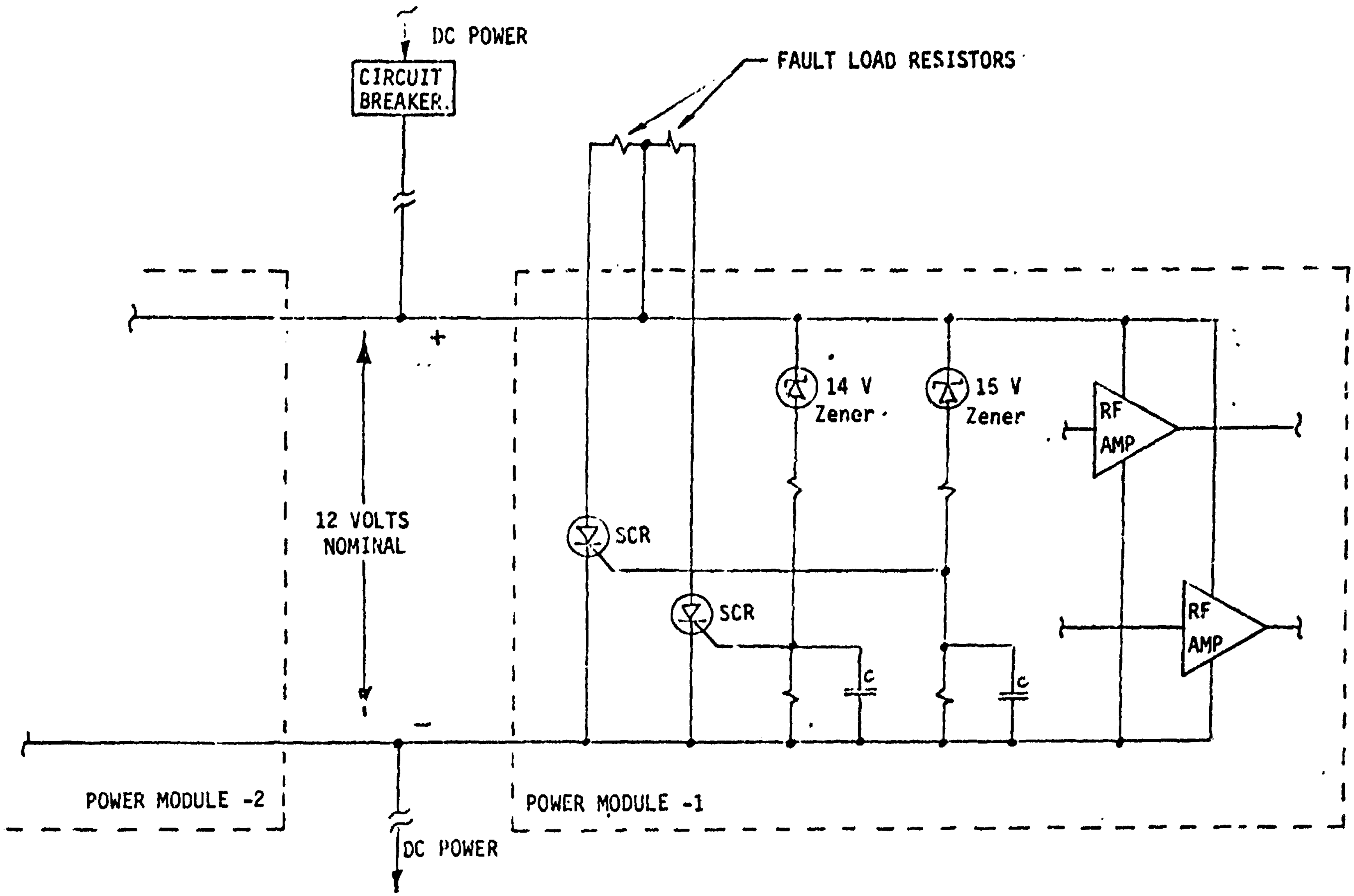
- THE FAULT RESISTOR'S HEAT IS RADIATED INTO SPACE.

- "OPEN" FAILURES ARE EASILY RECOGNIZABLE.

- A SHORTED POWER MODULE SHOULD BURN "OPEN" (2 AMPS) - ONE SUCH SHORT IN A CHAIN OF TWELVE MODULES WILL BE ACCOMMODATED.

POWER MODULE FAIL SAFE CIRCUITRY

PRELIMINARY



PANEL BUILDUP

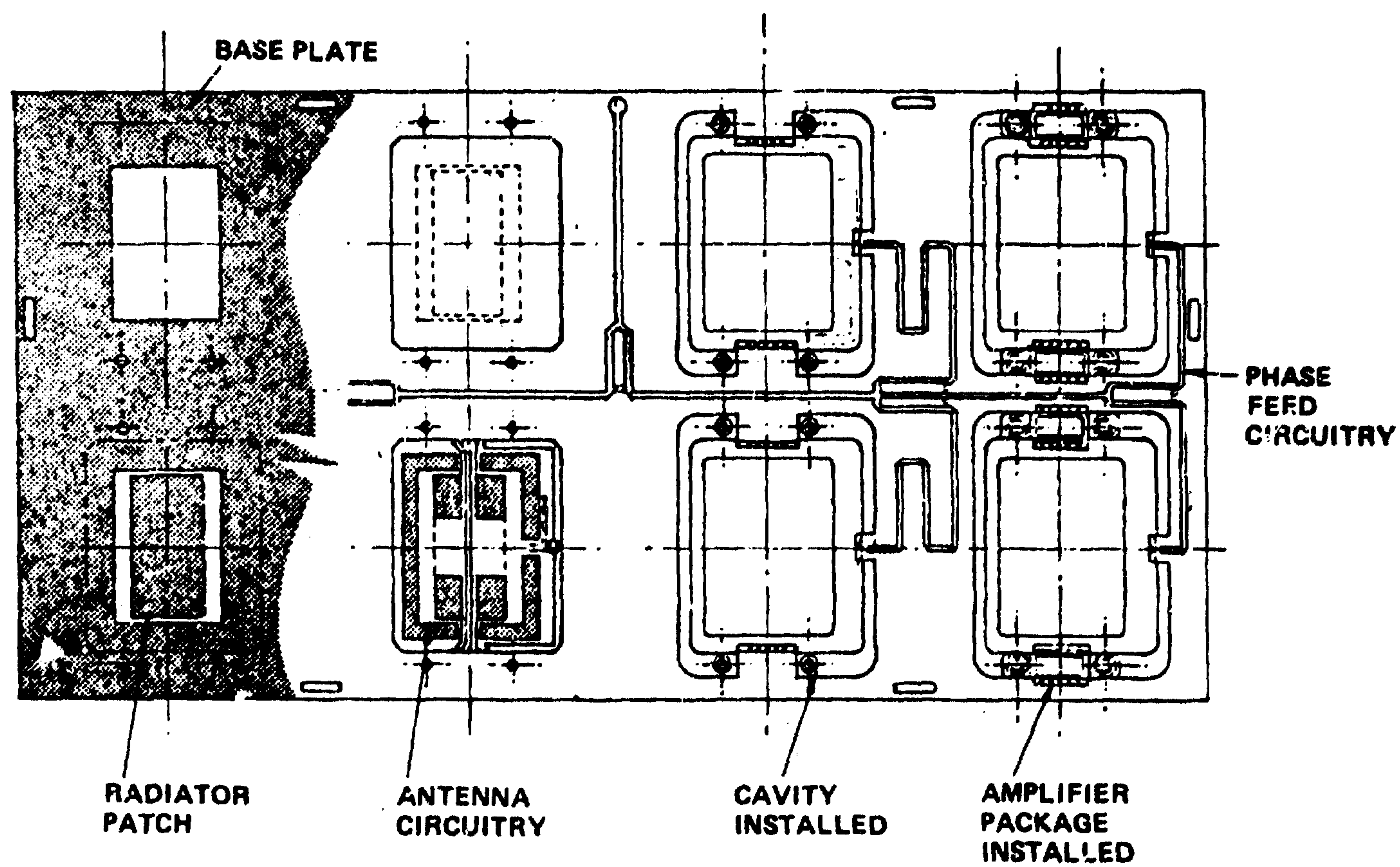
This chart shows a small segment of 64 module power amplifier panel and illustrates the construction sequence. Starting with the radiating face base-plate made of aluminum, the ceramic substrate containing the antenna circuitry on the backside and the radiator patch on the front is installed. Next, the backing cavities are added and the amplifier packages are installed. The phase feed and power supply circuitry is hooked up and the panel is ready for test.

Alternatively, the amplifier packages and phase feed circuitry could be installed and a single panel back cover could be added in one step.

BOEING SPS

Panel Buildup

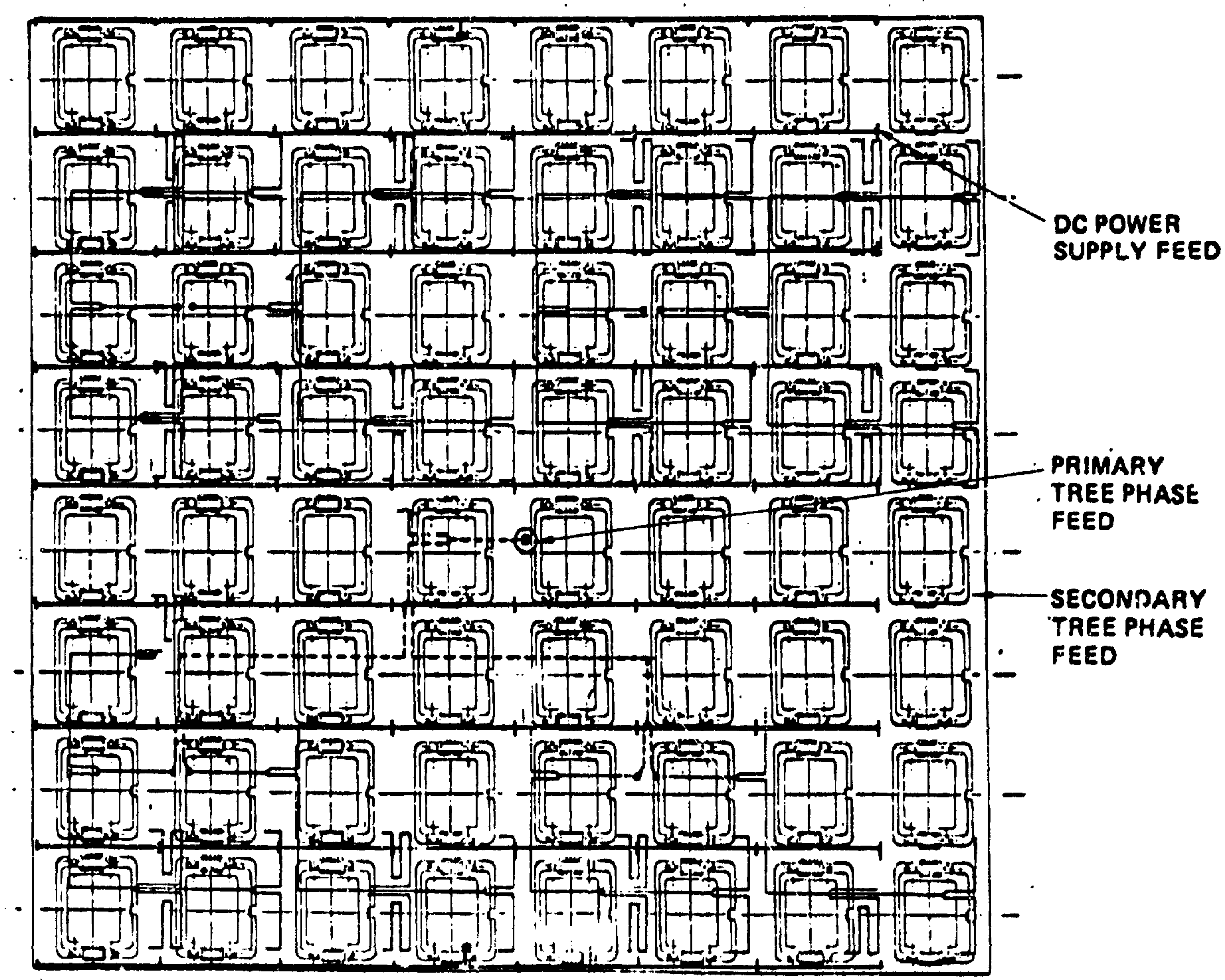
SPS-2868



64 MODULE PANEL LAYOUT

The complete layout of a panel is shown sans DC power supply feed and the primary phase feed tree. Those two networks are illustrated on the following two pages.

64-Modu' Panel Layout



STRING RELIABILITY ANALYSIS CONFIGURATION

The string configuration used in the reliability analysis consisted of 96 amplifiers in 12 rows of four modules each where each module had two output amplifiers. While this isn't exactly a current configuration it provides a good vehicle for quanitive analysis of the basic solid state transmitting antenna reliability problem. Simply stated the problem is how to allow some of the amplifiers in a series parallel configuration to fail without bringing down the rest as well.

The biggest problem is open circuits since for the solid state amplifiers short circuits will quickly burn out to become opens. In a series parallel configuration the effect of an open circuit is to provide more current to the elements in parallel with the opened element. In general, this means that those elements will have to take a somewhat higher voltage; i.e., their design must be uprated. The goal of the analysis is to determine how much voltage and current uprating of the amplifier modules is necessary to ensure a given reliability of the final configuration.

String Reliability Analysis Configuration

SPS-2553

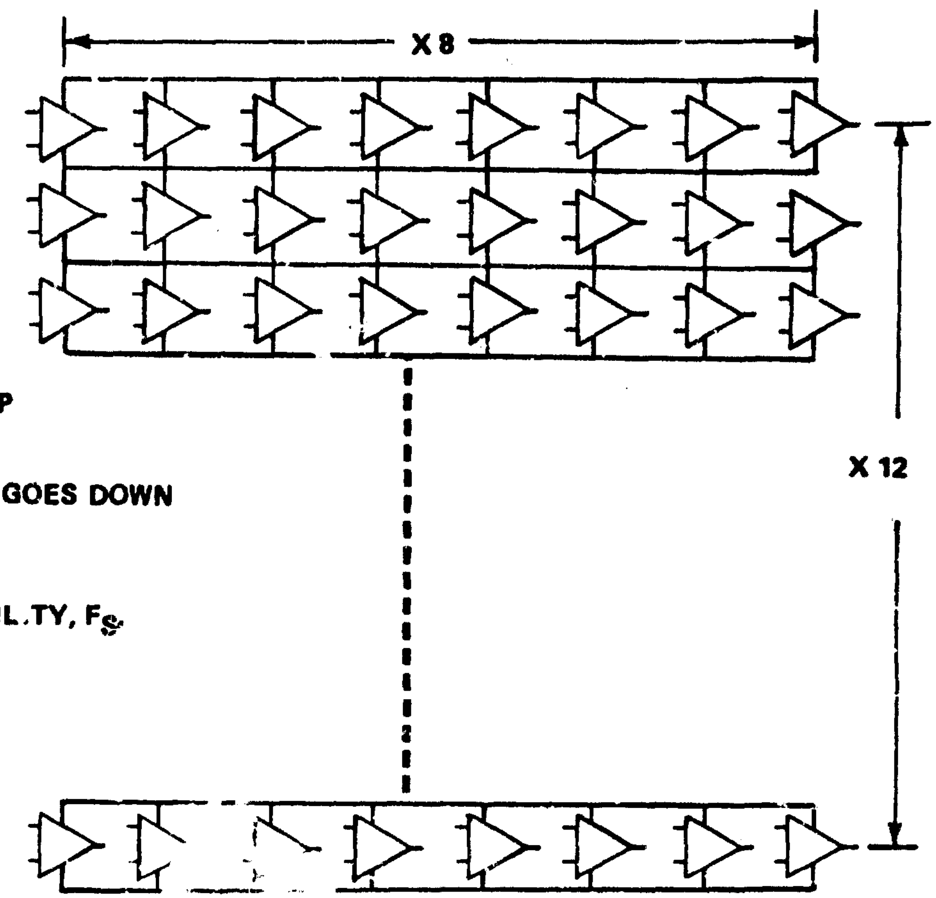
SERIES STRINGS OF 12 ROWS
- 4 MODULES PER ROW
- 2 AMPLIFIERS PER MODULE

SINGLE AMPLIFIER FAILURE PROBABILITY = F_P

IF > N AMPLIFIERS PER ROW FAIL STRING GOES DOWN
N=1,2

DESIRED RESULT IS STRING FAILURE PROBABILITY, F_S,
AS A FUNCTION OF F_P AND N

REWORK DESIGN UNTIL $F_S \ll F_P$



SOLAR CELL RELIABILITY MODEL

The problem discussed on the last page, while unusual in everyday electronics, is not unlike the solar cell reliability problem faced on the solar panels of the SPS. In fact, the solar cell reliability problem is somewhat more difficult because the strings are much longer.

SOLAR CELL RELIABILITY MODEL

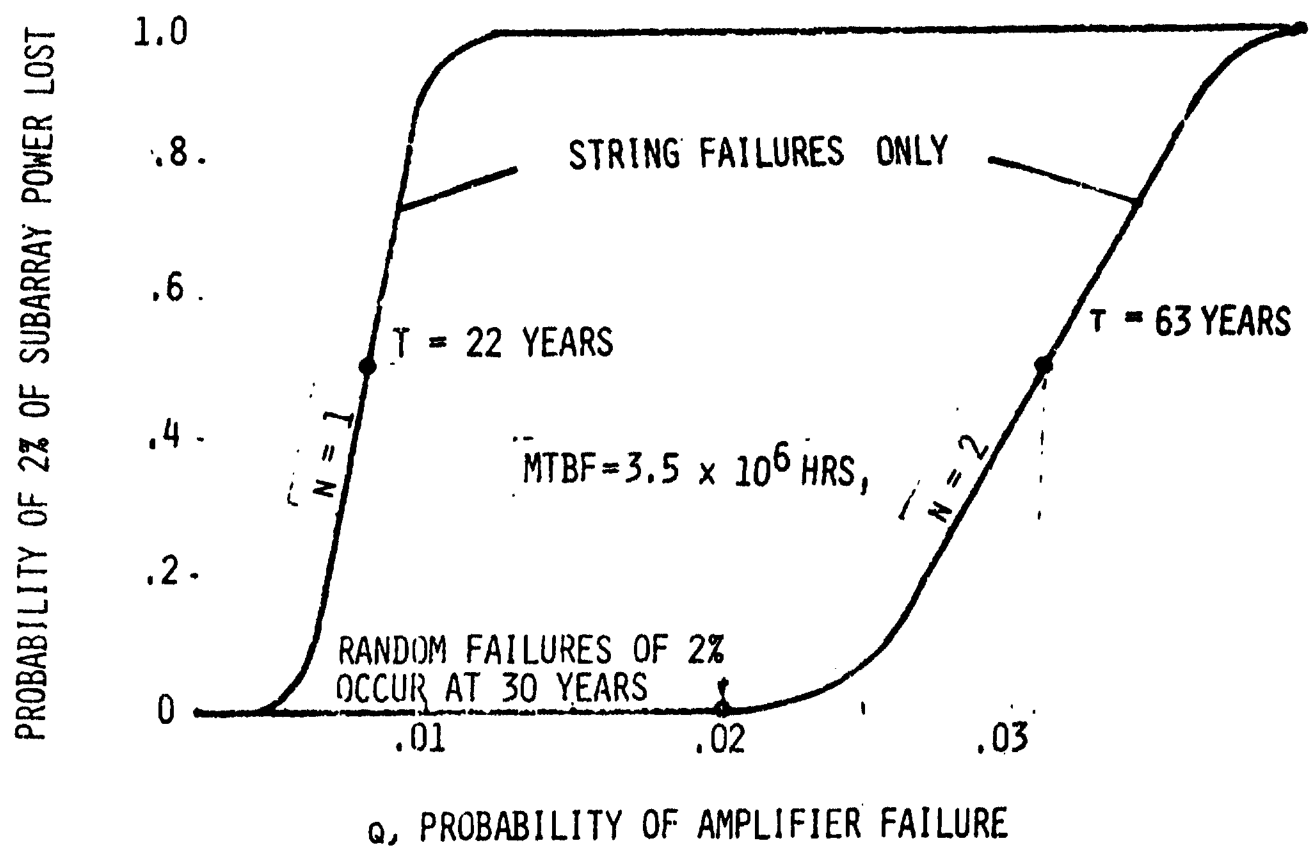
- NUMBER CELLS 21 BILLION
  19,072 STRINGS, EACH 80,000 CELLS OF UNITS OF 14 IN PARALLEL
- EACH STRING CAN LOOSE 4 OUT OF 14 UNITS BEFORE IT IS CONSIDERED FAILED (REVERSE BIAS ACROSS CELL)
- FOR A CELL MTBF OF 10^8 HRS. THERE ARE 0.36 STRING FAILURES IN 30 YEARS
- ARRAY IS INITIALLY OVERSIZED TO COMPENSATE FOR THESE FAILURES

SOLID STATE SPS CHAIN RELIABILITY

It was found that with eight amplifier rows and 12-row strings it was necessary to design the amplifiers to be able to withstand the additional voltage and current causes by having two of the amplifiers in the row fail. I.e., they must able to operate successfully carrying one third more current than in a normal no-failure situation.

SOLID STATE SPS CHAIN RELIABILITY

CONFIGURATION: 8 AMPLIFIERS PER ROW, ONE OR TWO MAY FAIL (N=1,2)
12 ROWS PER STRING 432 STRINGS PER SUBARRAY
LOG NORMAL DISTRIBUTION



PATTERN STUDIES

Antenna pattern studies have been done by numerical integration of patterns of individual subarrays (as in the case of modmain and tiltmain) and at the less detailed but more analytically tractable level of radial aperture illumination functions. A recently developed axis-symmetric anntena pattern analysis program has proved useful in studying the effects of various apterature illumination functions. The sidelobe suppression ring studies illustrated here are an example.

With these two possible levels of antenna pattern simulation, system simulation support studies may be done with a minimum of difficulty.

PATTERN STUDIES

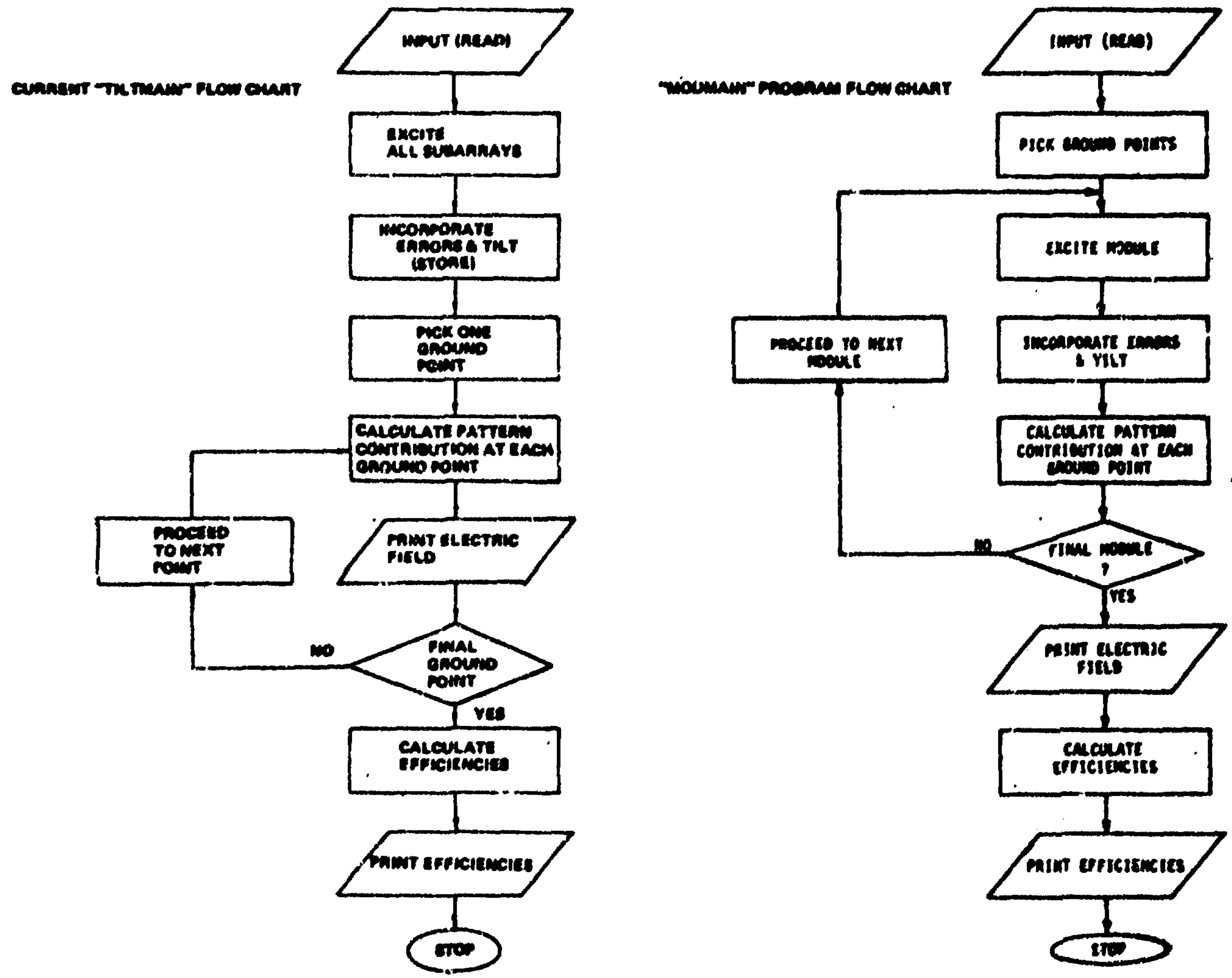
- SPS MODULE LEVEL SIMULATION
  - MODMAIN PROGRAM STATUS
  - INITIAL COMPARISON WITH TILTMAIN
- ILLUMINATION FUNCTION TRADE STUDY
  - SPS ANTENNA PROGRAM
  - SUPPRESSOR RING STUDIES
- SYSTEM SIMULATION SUPPORT STUDIES

COMPUTER PROGRAM FLOW COMPARISON

The basic differences between the tiltmain and modmain calculation procedures are shown. Because modmain does not store all the subarray excitations, it requires much less computer memory storage space to run. This means that modmain can model the transmitting array in much more detail than tiltmain. An example of this is shown on the following chart which illustrates how modmain was able to calculate the grating lobes from the power modules within the subarrays as well as the grating lobes due to the subarrays themselves. Tiltmain does not have this capability.

Computer Program Flow Comparison

SPS-2580



MODMAIN IMPLEMENTATION

MODMAIN has a number of features that make it more flexible and easier to use than previous SPS large transmitting array analysis programs.

MODMAIN IMPLEMENTATION

- o INCORPORATED PROGRAMMING LOOP WHICH DECIDES THE SIZE AND NUMBER OF KLYSTRON MODULES FOR EACH SUBARRAY.
- o INCORPORATED GRATING LOBE SEARCH ROUTINE WITH THE OPTION TO SPECIFY THE LENGTH OF A MODULE ON WHICH TO BASE THE POSITION OF THE GRATING LOBES.
- o ADDED PROGRAMMING TO COUNT THE NUMBER OF SUBARRAYS IN EACH OF THE 10 QUANTIZED LEVELS SO AS TO HAVE A CHECK BETWEEN THE SIMULATION PROGRAM AND THE REFERENCE DESIGN.
- o DELETED OUTDATED PROGRAMMING OPTIONS IN ORDER TO INCREASE PROGRAM FLOW CLARITY AND REDUCE RUN TIME.
- o ASSEMBLED INITIAL DRAFT OF MODMAIN PROGRAM USERS' MANUAL

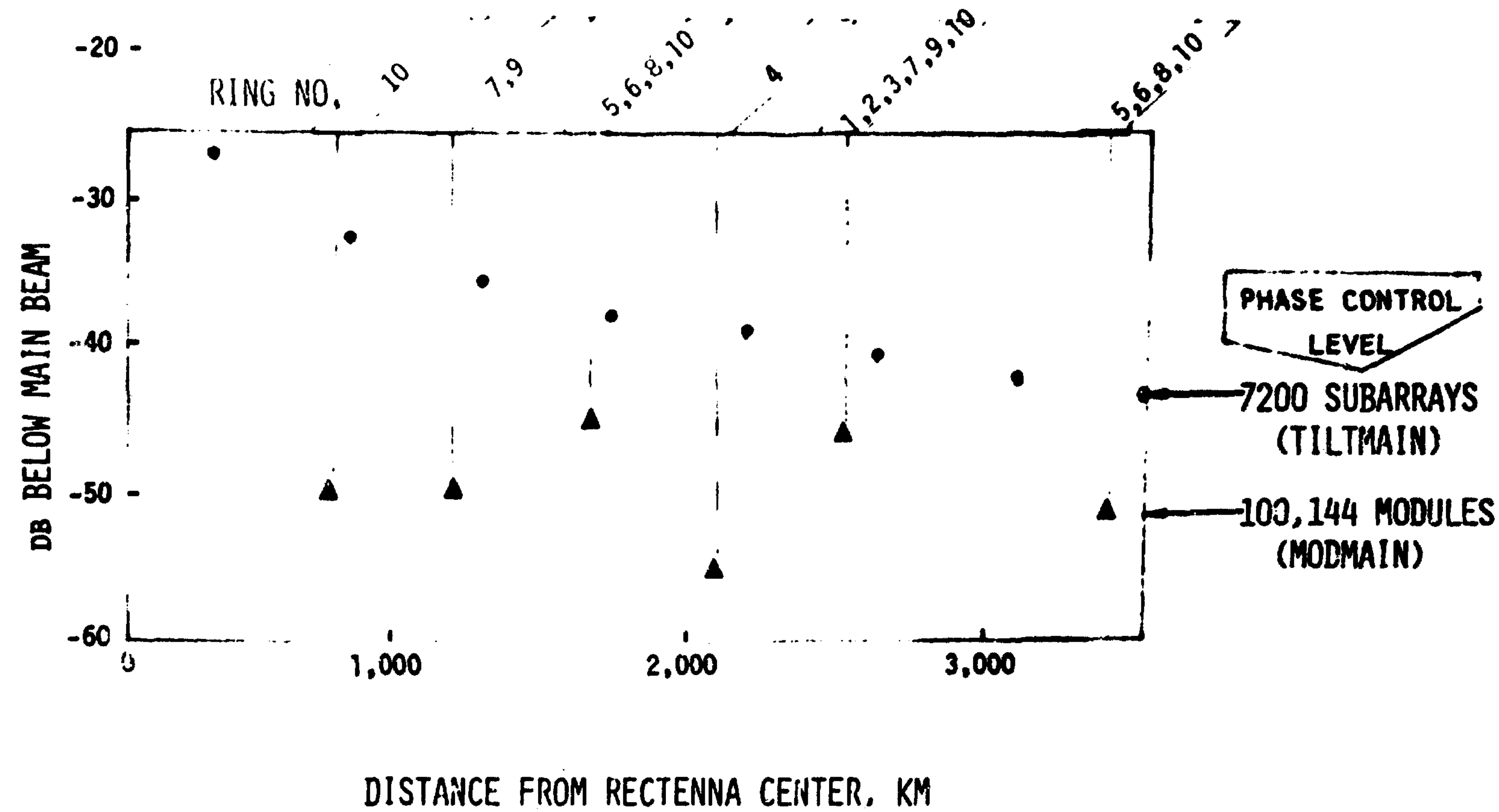
EFFECT OF MODULE SIZE ON GRATING LOBE LEVEL

o	MODMAIN COMPARISON WITH TILTMAIN:	AMPLITUDE ERRORS	1db
	10m x 10m.	PHASE ERRORS	10^{o}
		FAILURES	2%
		SUBARRAY TILT (RANDOM)	2 arcmin
		SPACETENNA TILT (SYSTEMATIC)	2 arcmin

o PREDICTED GRATING LOBE POSITIONS WERE VERIFIED BY MODMAIN.

EFFECT OF MODULE SIZE ON GRATING LOBE LEVEL

(SYSTEMATIC TILT = 2 ARC MIN.)



AXISYMMETRIC ARRAY PATTERN STUDIES

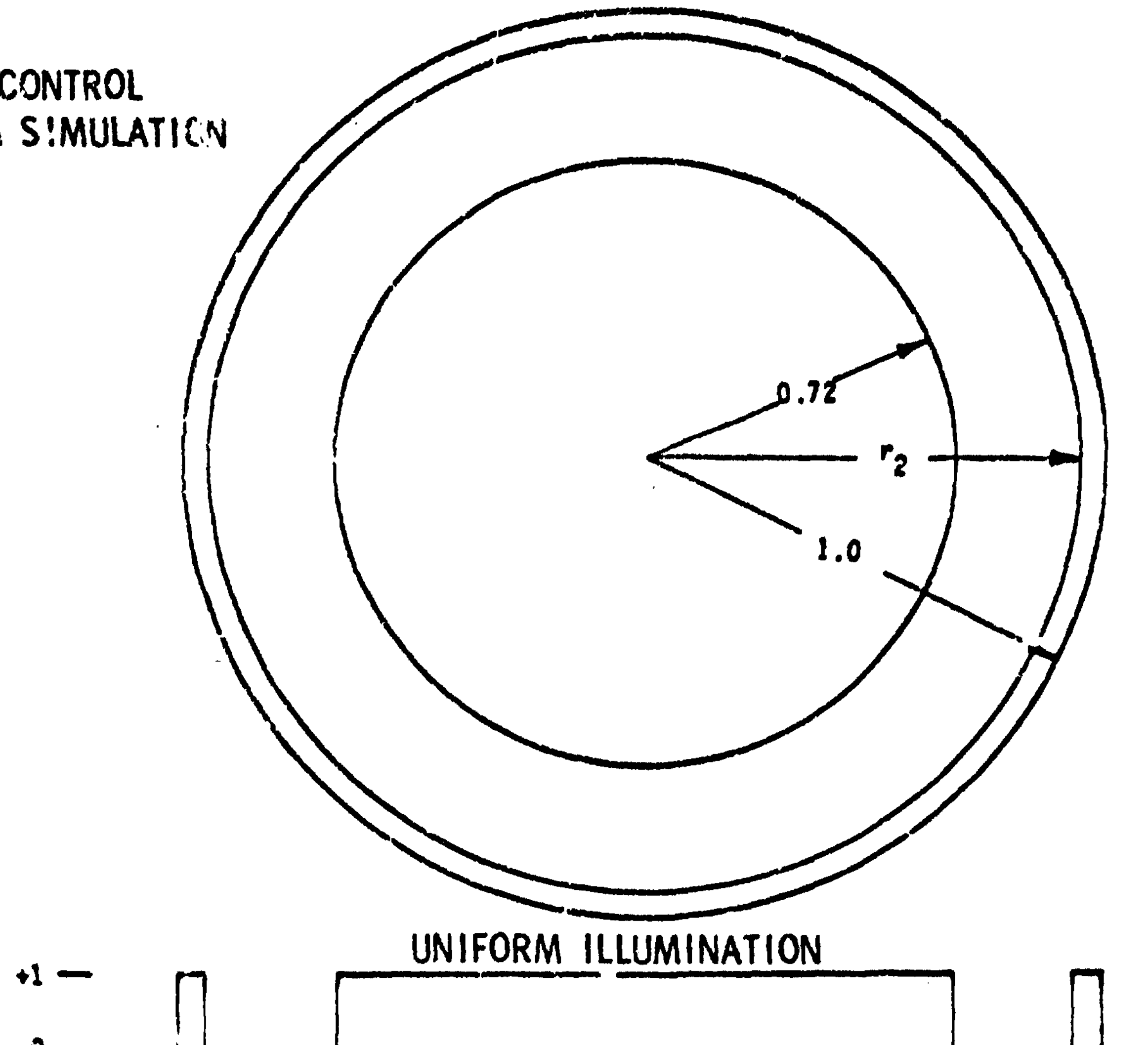
The effect of adding rings around a transmitting antenna in order to square up the beam and/or suppress side lobes was investigated. Although the rings studied today are not economic from an SPS cost of electricity viewpoint, they have produced interesting patterns which are illustrated in this section.

AXISYMMETRIC ARRAY PATTERN STUDIES

UNIFORMLY EXCITED ARRAY WITH IN-PHASE SIDE LOBE SUPPRESSOR RING

An aperture with the indicated illumination was modeled, it provided the efficiency and power pattern shown on the following chart.

UNIFORMLY EXCITED ARRAY WITH IN-PHASE SIDELOBE SUPPRESSOR RING



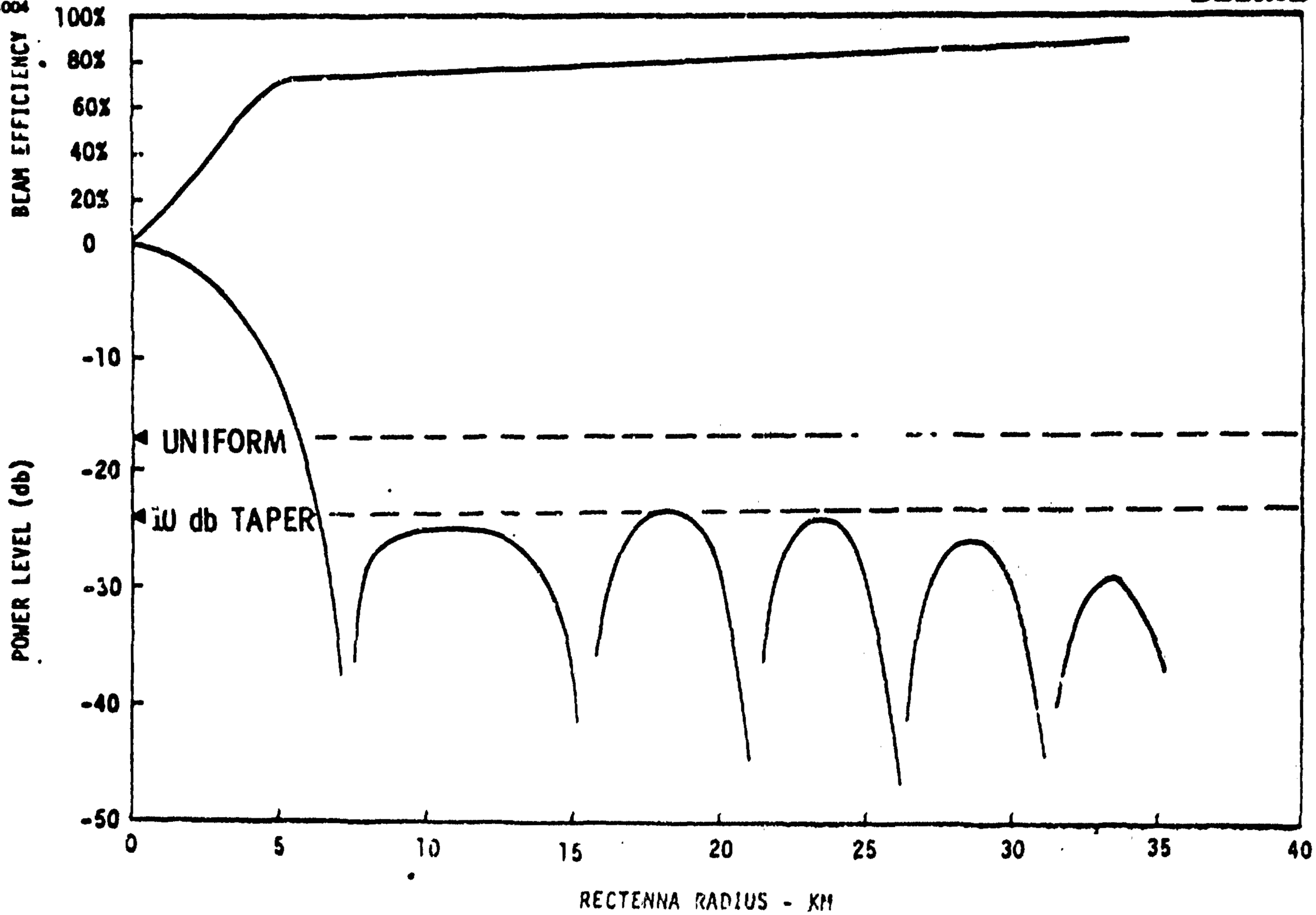
SIDE LOBE AND EFFICIENCY OF UNIFORM ARRAY WITH IN-PHASE SIDE LOBE SUPPRESSOR RING

When the side lobe suppressor ring was adjusted to give side lobes as low as those of the 10db taper Gaussian the beam efficiency was 80%.

SIDELOBE LEVEL & EFFICIENCY OF UNIFORM ARRAY WITH IN-PHASE SIDELOBE SUPPRESSOR RING

$R_2 = .94$

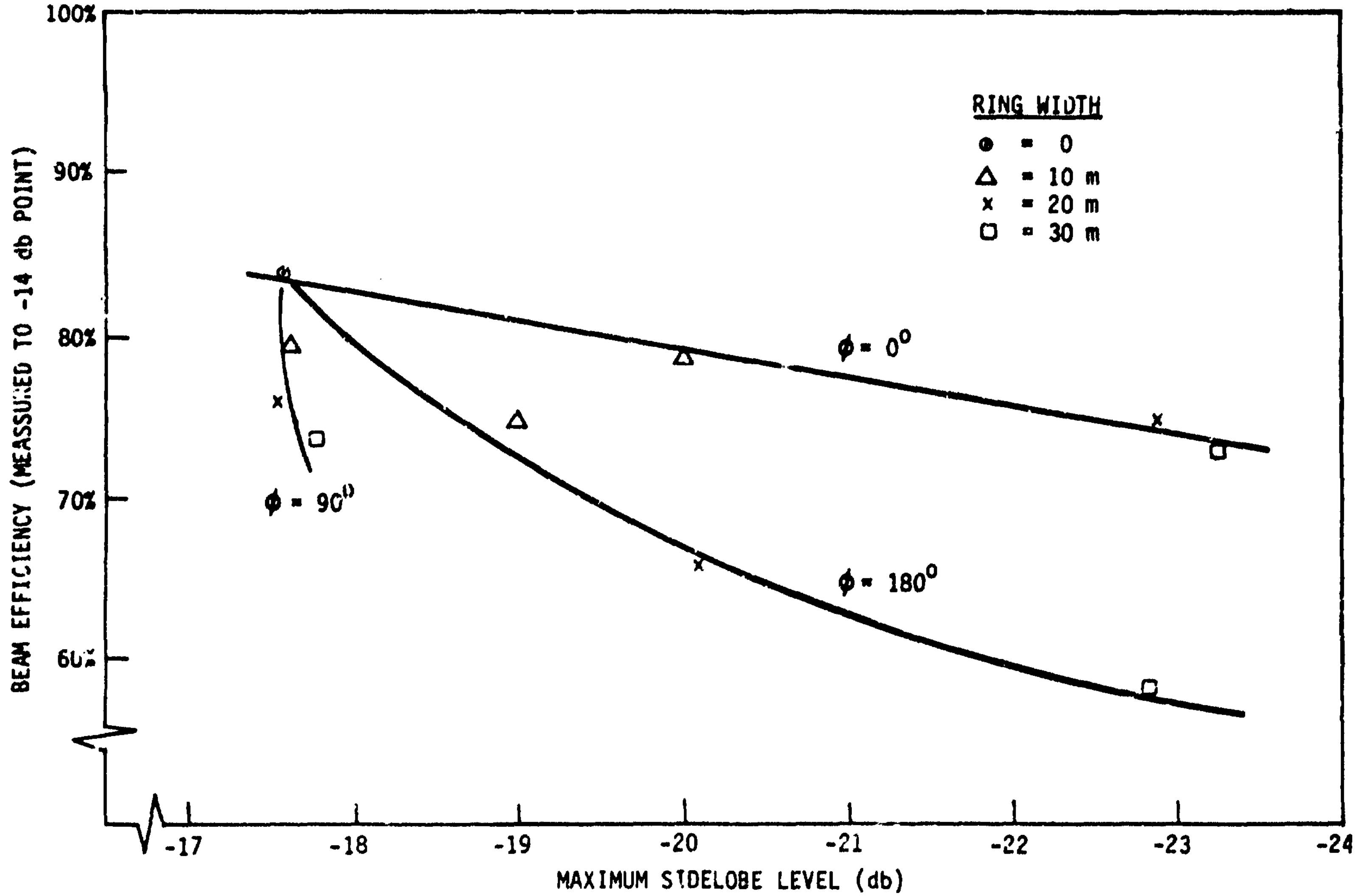
SPS-3004



EFFICIENCY VS SIDE LOBE LEVEL OF UNIFORMLY EXCITED ARRAY WITH IN-PHASE SIDE LOBE SUPPRESSOR RING

There a e fairly direct trade-offs of beam efficiency and maximum side lobe level with uniform rings of various widths and facings. Note that the efficiencies are all worse than that of the uniformly excited array with no ring, which has an 83% efficiency at the -14 dB point.

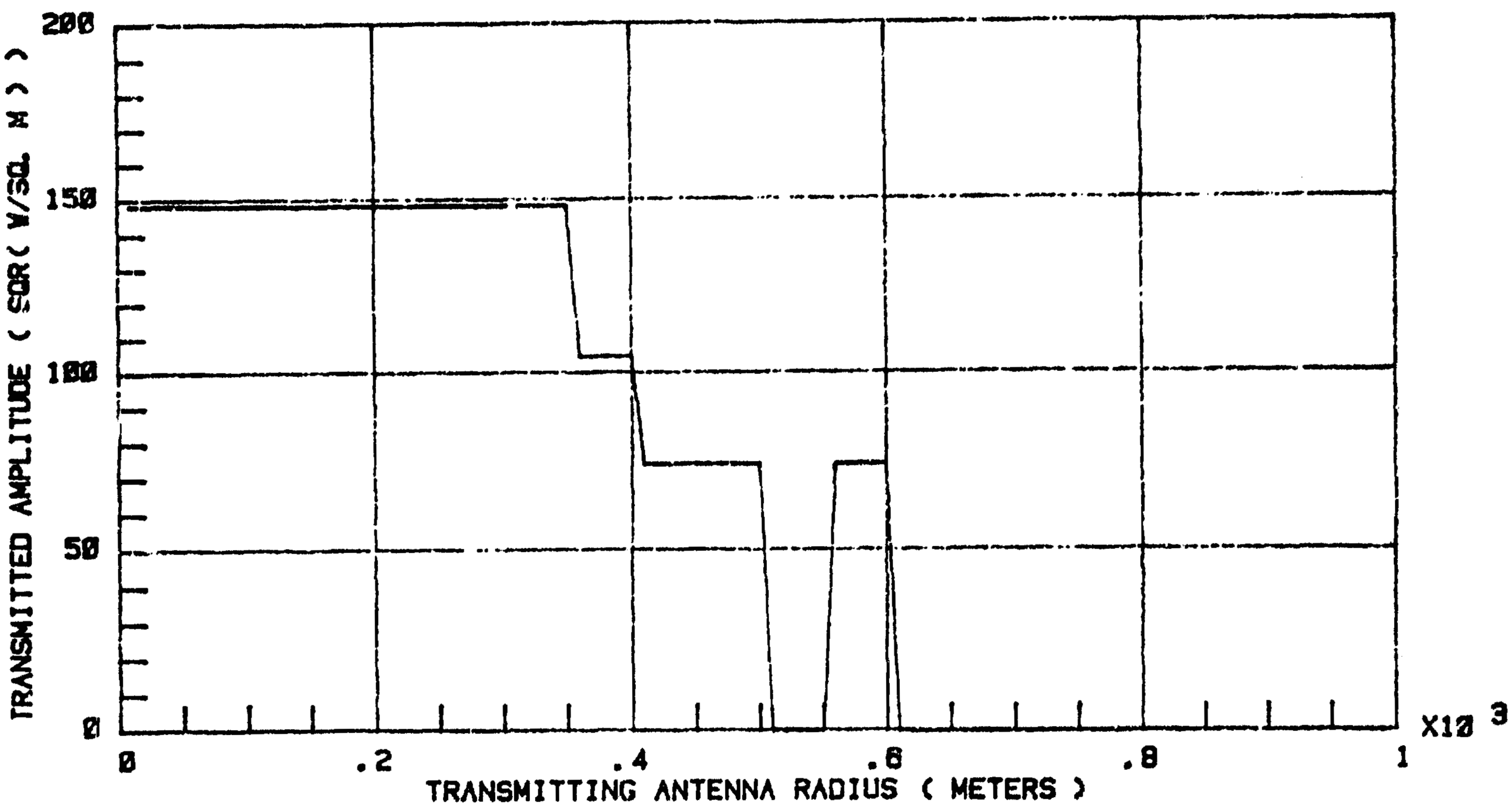
EFFICIENCY VS SIDELOBE LEVEL OF UNIFORMLY EXCITED ARRAY WITH IN-PHASE SIDELOBE SUPPRESSOR RING



IMPROVED IN-PHASE SUPPRESSOR RING: ILLUMINATION FUNCTION

It was found that tapering the central transmitting aperature distribution in three steps and reducing the amplitude level of the ring improved efficiency greatly. However, it does not outperform the base line 10 db Gaussian.

IMPROVED IN-PHASE SUPPRESSOR RING: ILLUMINATION FUNCTION

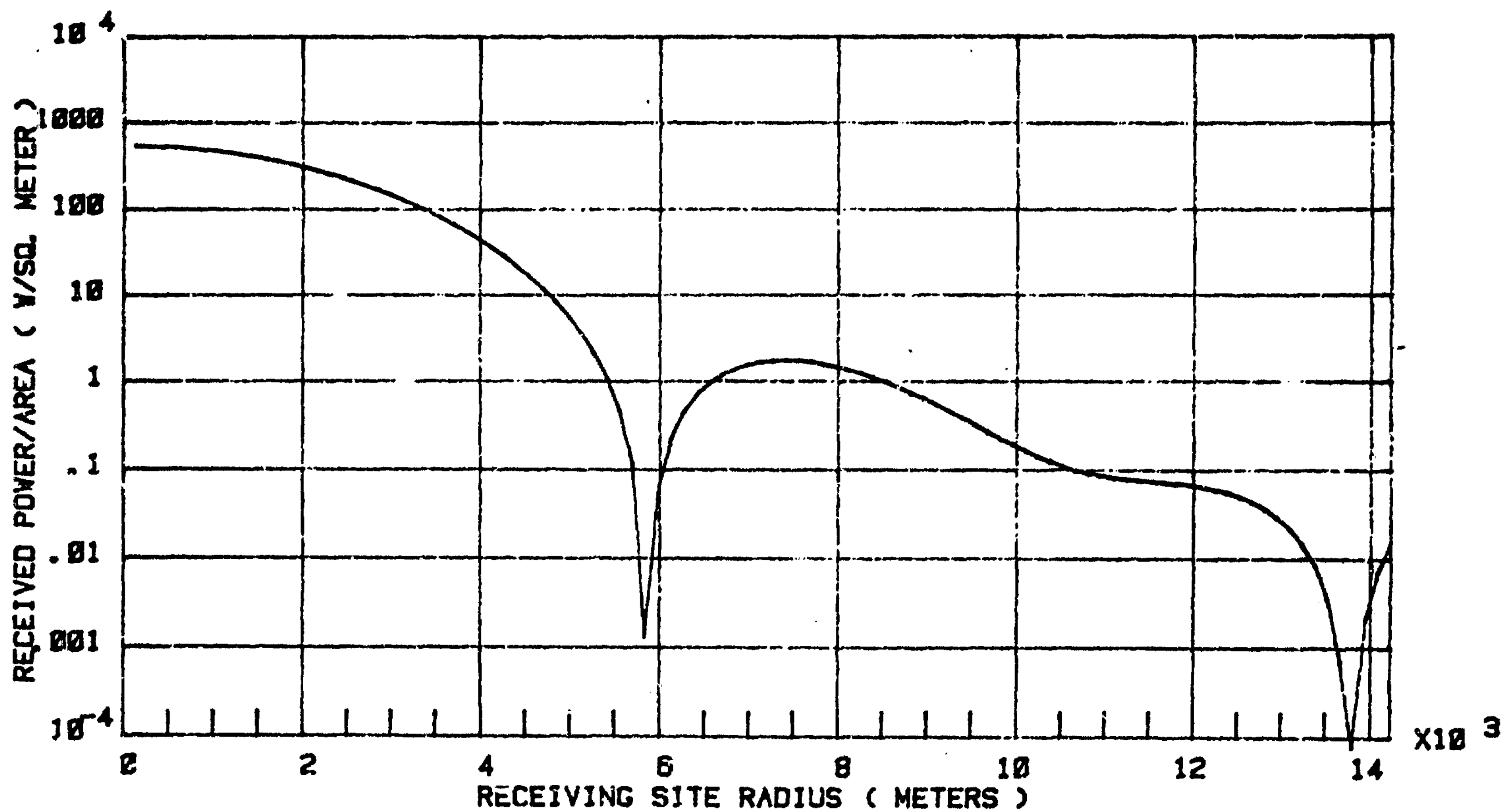


IMPROVED IN-PHASE SUPPRESSOR RING: SIDE LOBE SUPPRESSION

The receive power per unit area pattern of the transmitted pattern shown on the previous page was able to produce side lobes 24.7dB down from the peak power point.

SPS-3013

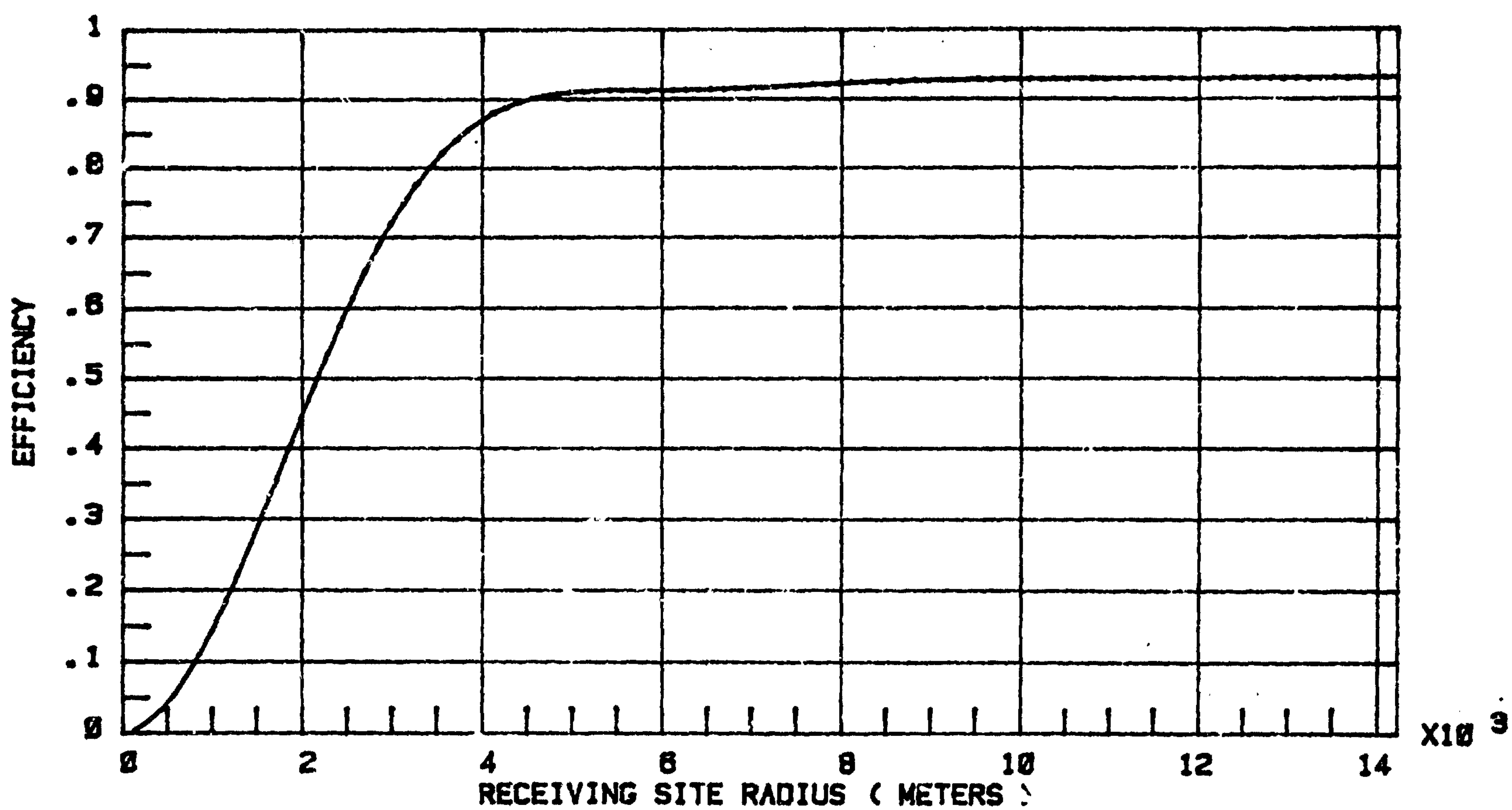
IMPROVED IN-PHASE SUPPRESSOR RING: SIDELOBE SUPPRESSION



IMPROVED IN-PHASE SUPPRESSOR RING: EFFICIENCY

The efficiency of the improved in-phase suppressor ring pattern was over 90%.

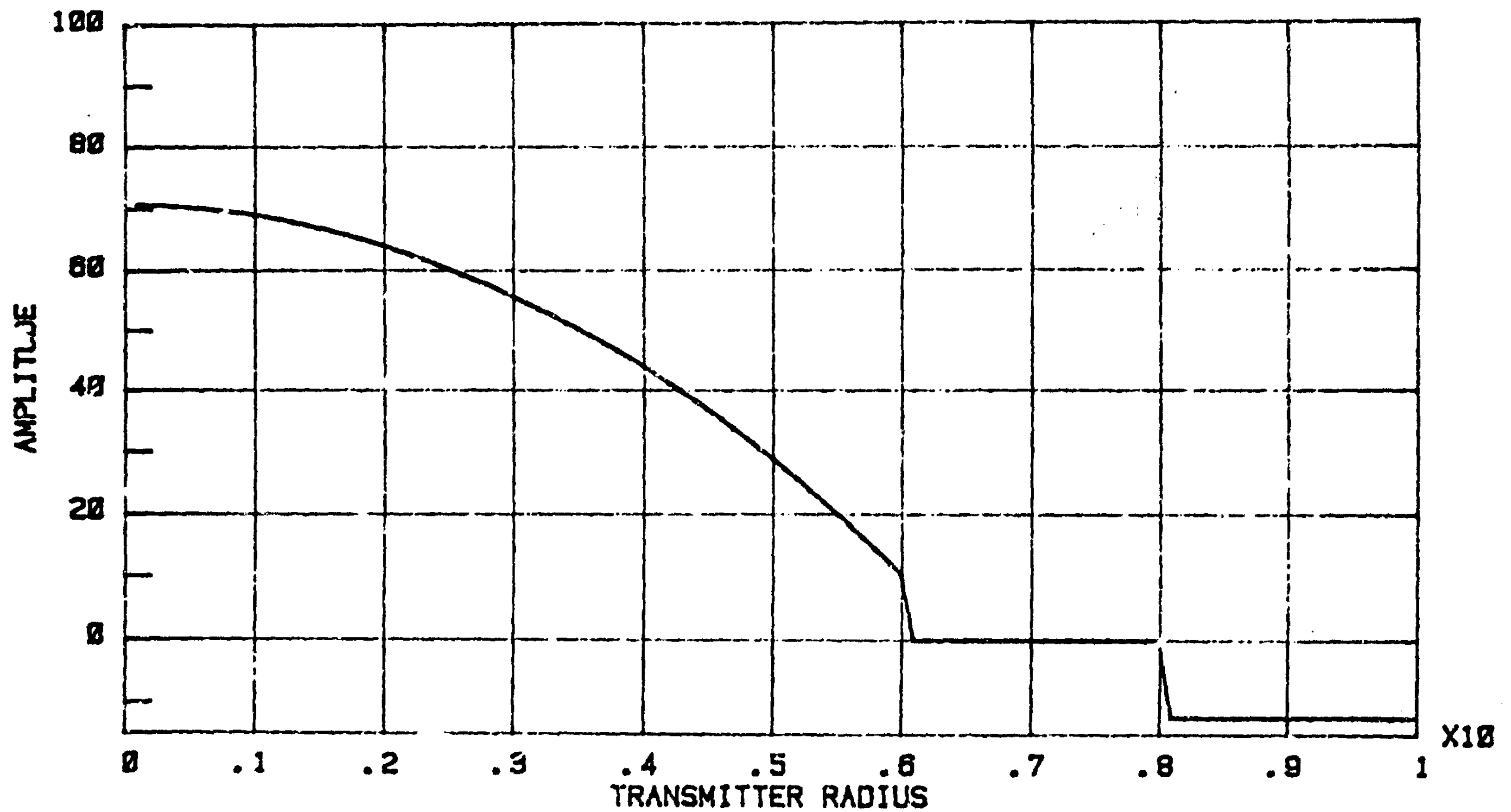
IMPROVED IN-PHASE SUPPRESSOR RING: EFFICIENCY



REVERSE PHASE RING : ILLUMINATION AMPLITUDE

This pattern was investigated as an alternate to the standard solid state transmitting antenna pattern which has a 5.5 kilowatt per square meter peak power.

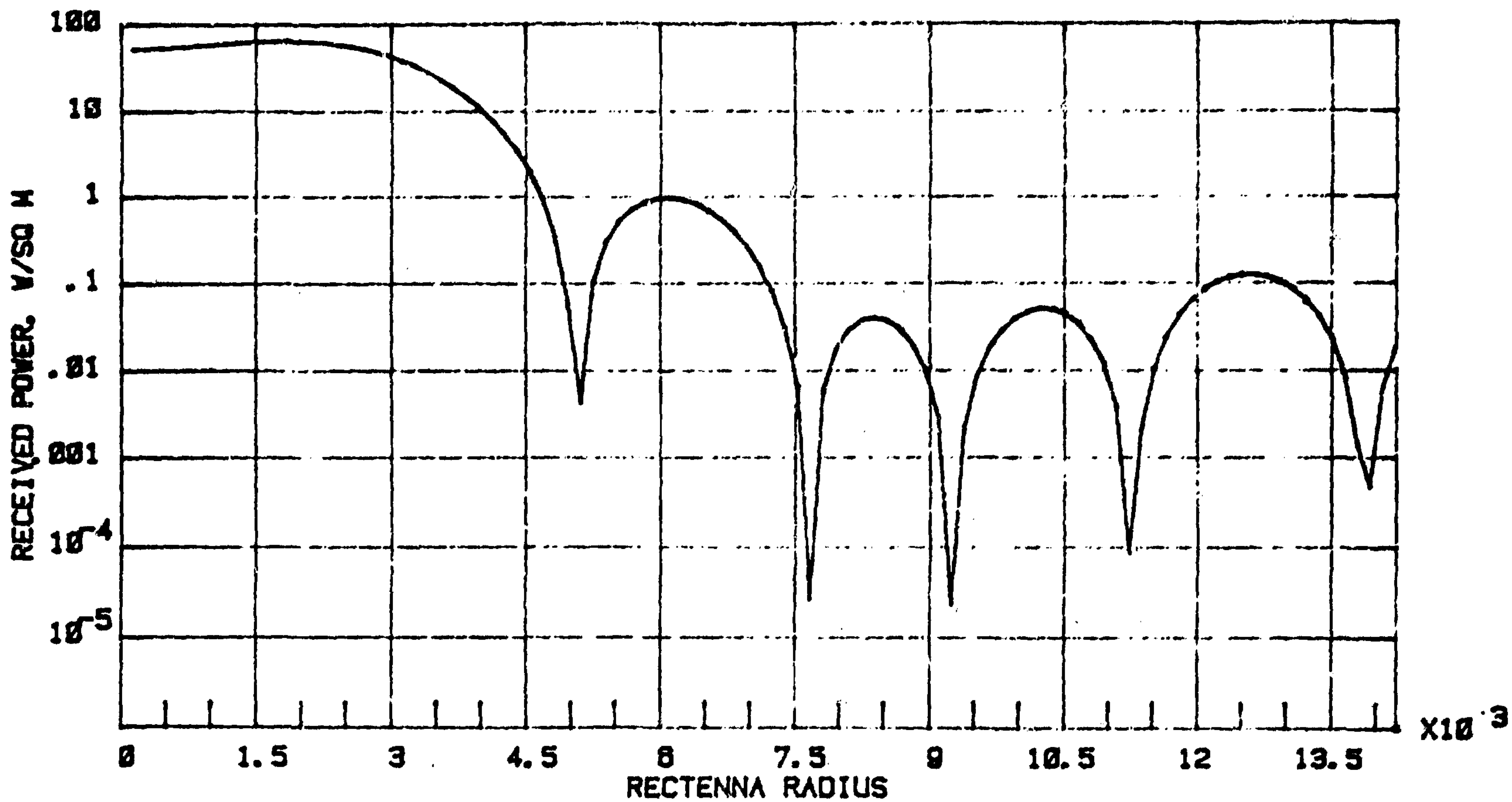
REVERSE PHASE RING ILLUMINATION AMPLITUDE



REVERSE PHASE RING: BEAM SHAPE

Adding the ring in the appropriate fashion allowed the received power pattern to be squared up considerably. However, the first side lobe also rose.

REVERSE PHASE RING: BEAM SHAPE

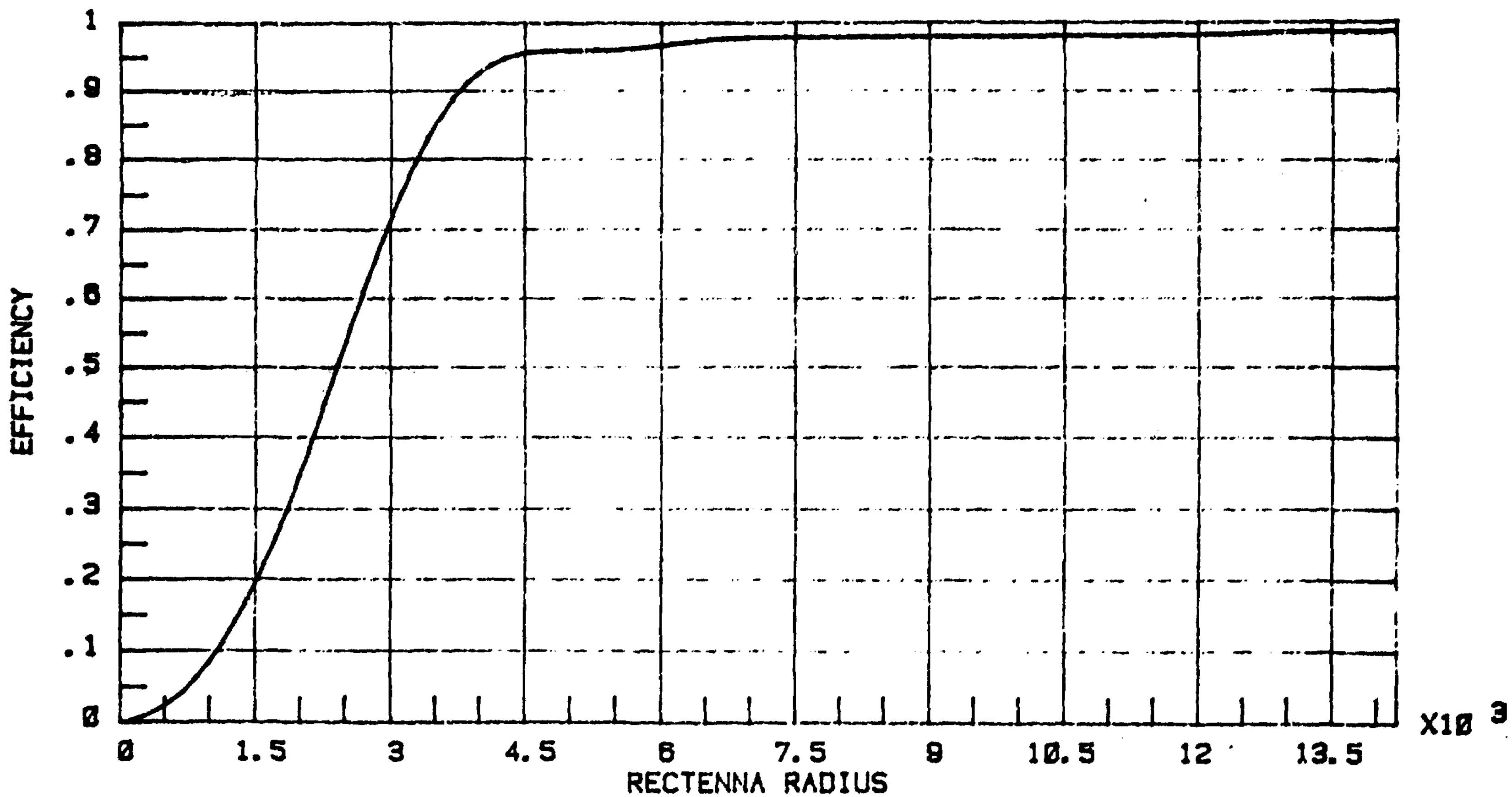


REVERSE PHASE RING: EFFICIENCY

The efficiency of the reverse phase ring is substantially that of the base line 9.5426 Gaussian.

REVERSE PHASE RING: EFFICIENCY

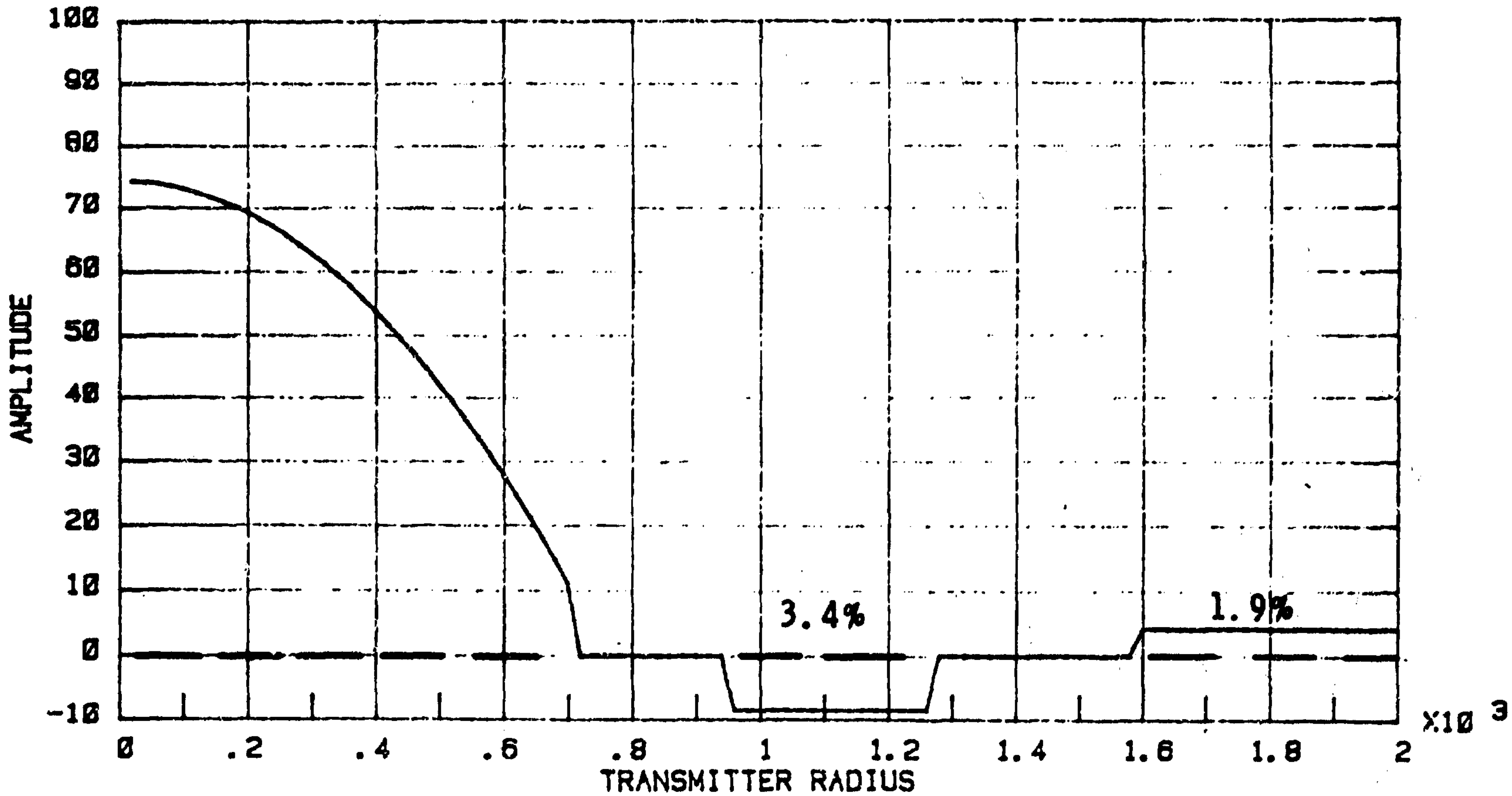
SPS-3009



DUAL RING: ILLUMINATION AMPLITUDE

In order to bring the side lobe down, a second ring was added in a radius of between 1.6 and 2 kilometers from the transmitting antenna center. This ring only contained 1.9% of the total power while the reverse phase ring contained 3.4% of the total power. Although the ring power itself is small, the rings allow an increase of about 40% in the power transfer of an intensity-limited link by suppressing the central leak of the received power pattern. These rings represent a simple reverse-phase method of increasing link power. If continuous (or nearly continuous) phase tapers can be employed, equivalent results may be obtained with smaller aperture areas and diameters.

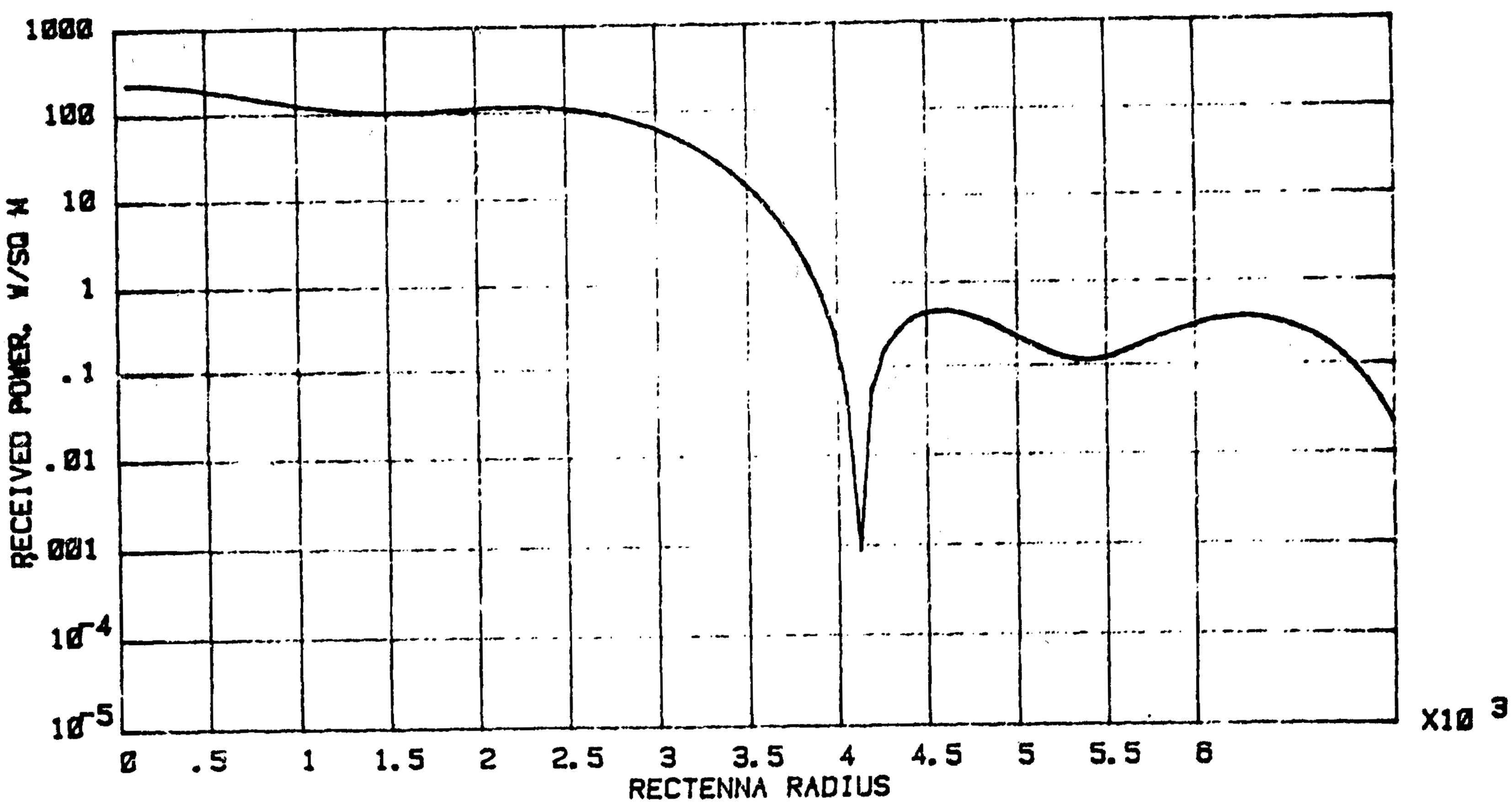
DUAL RING: ILLUMINATION AMPLITUDE



DUAL RING: POWER PATTERN

The received power pattern of the dual ring meets side lobe criteria and has a nice square central peak.

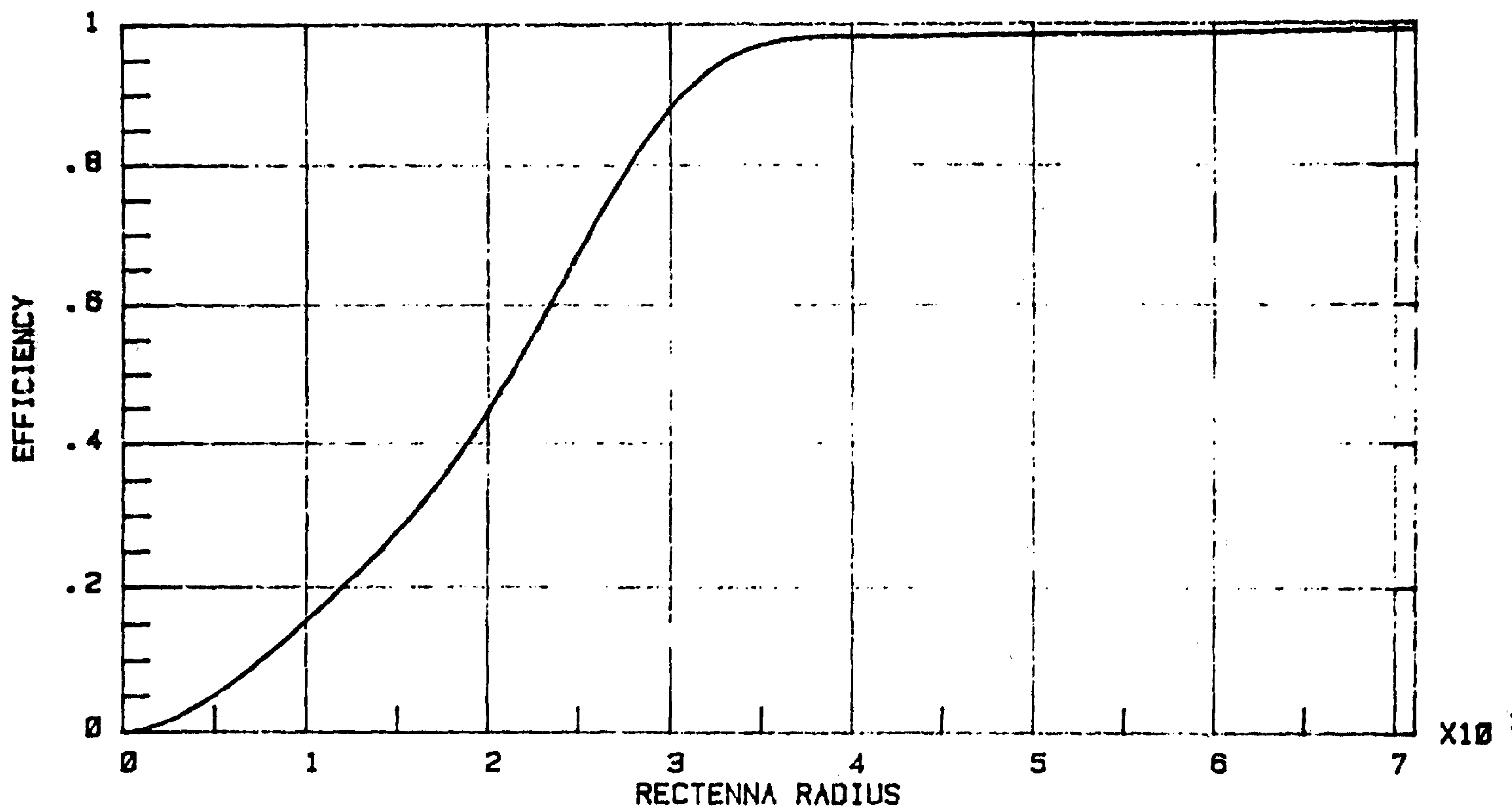
DUAL RING: POWER PATTERN



DUAL RING: EFFICIENCY

The efficiency of the dual ring pattern is over 98%.

DUAL RING: EFFICIENCY



LINK POWER VERSUS EFFICIENCY

The achievable SPS link power versus beam efficiency to the -14dB point was plotted for a number of patterns and compared with the base line 9.54dB Gaussian. All the common patterns seen in the SPS literature appear to have link powers within a factor of 2 of that of the 9.54dB Gaussian.

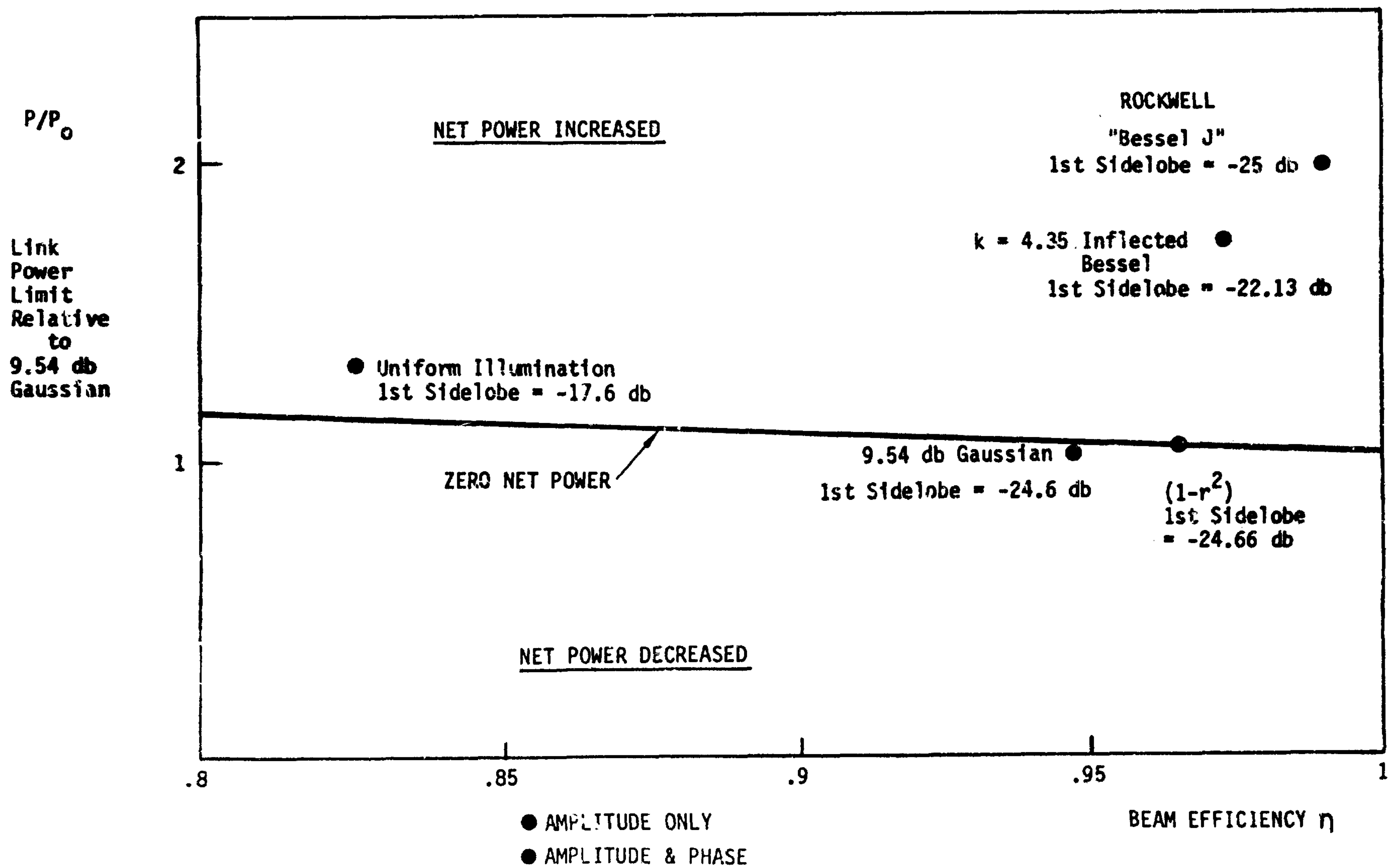
Very high power (greater than 20 Gw) links, employing large apertures with amplitude and phase taper, and for which the rectenna is in the near field of the transmitter, are possible but have received relatively little investigation.

SPS

SPS-3002

LINK POWER VS EFFICIENCY

BOEING

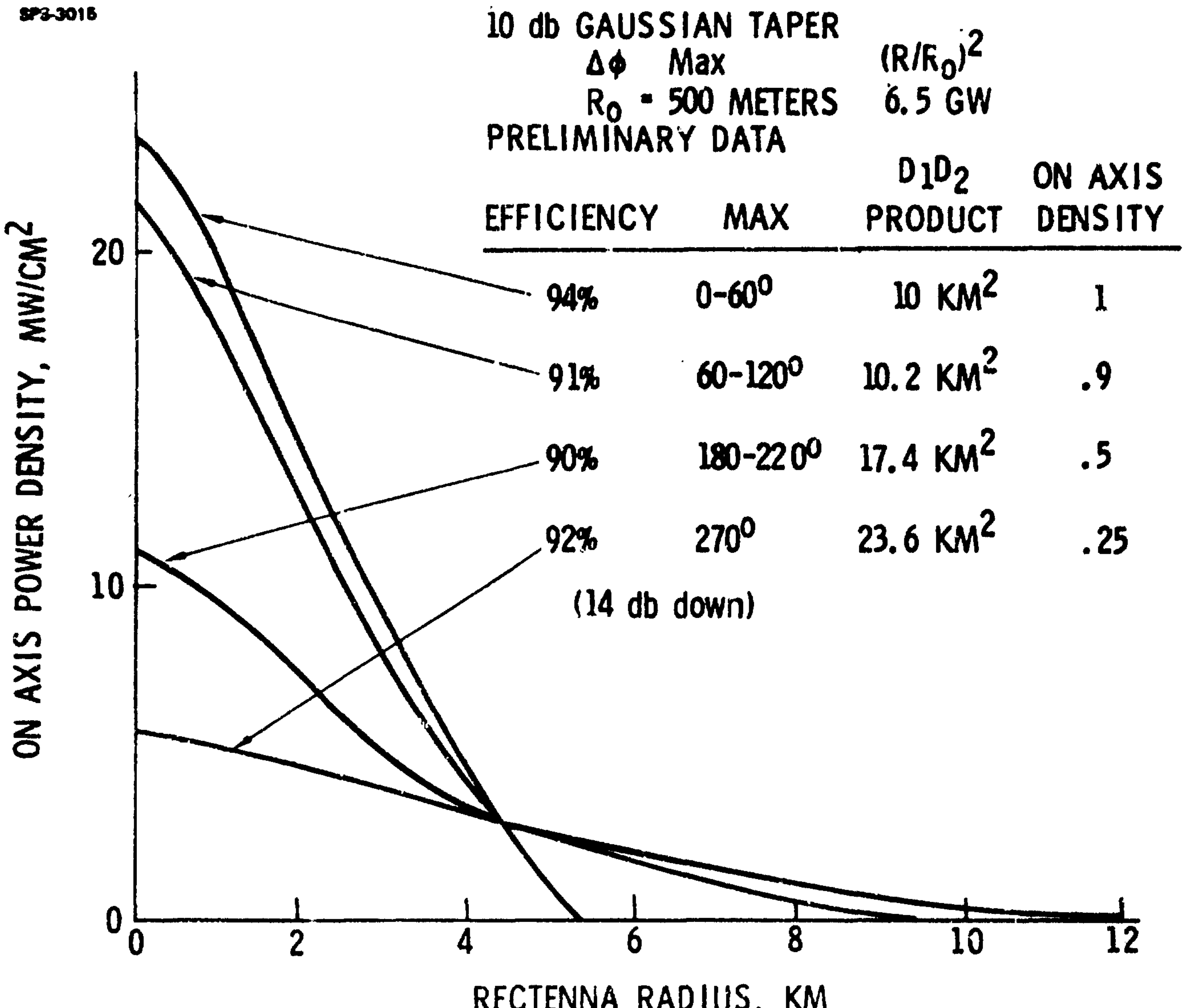


FEASIBILITY OF BEAM SPREADING BY PHASE DEFOCUSING

By adding a quadratic phase taper to the 10dB Gaussian base line pattern, one can reduce the on-axis power density and spread the pattern somewhat. However, this degrades the efficiency by several percent.

FEASIBILITY OF BEAM SPREADING BY PHASE DEFOCUSING

SPS-3015



SPS ARRAY SIMULATION

A number of different reference system and axisymmetric array simulation problems and trades remain to be worked. These are listed.

SPS ARRAY SIMULATION

- o REFERENCE SYSTEM SIMULATION
  - o PHASE CONTROL SIMULATION
    - MODEL DISTRIBUTION TREE
    - LEVEL AT WHICH PHASE CONTROL IS EXERCISED
    - MODEL DIFFERENT PHASE DISTRIBUTIONS
  - o *IMPACT OF ANTENNA DEFORMATION*
    - INCORPORATE SUBARRAY OFFSET CAPABILITY
  - o DETAILED SPS DESIGN UTILIZING MODMAIN AND TILTMAIN
    - EFFECT OF SUBARRAY QUANTIZATION ON SIDELOBE ROLL-OFF
    - STUDY EDGE EFFECTS USING CIRCULAR QUANTIZATION
    - COMPARE SOLID STATE AND KLYSTRON SPS DESIGNS
  - o STUDY EFFECTS OF CONTROLLED BEAM DEFOCUSING
    - IMPACT ON POWER SIZING AND EFFICIENCY
- o AXISYMMETRIC ARRAY SIMULATION
  - o EVALUATE ALTERNATE ILLUMINATION FUNCTIONS
    - AMPLITUDE ONLY
    - AMPLITUDE AND PHASE

PHASE CONTROL FLIGHT TEST CONCEPTS

Three key elements in the verification of the phase control system are one-way path experiments for ionospheric model verification, verification of the phase control flight system, and actual SPS demonstration. One-way path experiments may be done with existing satellites. However, detailed ionispheric model verification probably requires a large aperture low power satellite and an inverted transmit array. It is possible that linear arrays may suffice, both in space and on the ground for signal pattern verification. Finally, for the SPS demonstrator, the augmented aperture concept, which allows a lower transmitted power to verify SPS power level beams, should be investigated because of its possible cost savings.

PHASE CONTROL FLIGHT TESTS CONCEPTS

- <u>ONE WAY PATH EXPERIMENT</u>
  - EXISTING SATELLITE TESTS
- <u>IONOSPHERIC MODEL VERIFICATION</u>
  - LARGE APERTURE LOW POWER SATELLITE
  - RECEIVE ONLY LINE ARRAY
  - INVERTED TRANSMIT ARRAY
- <u>SPS DEMONSTRATOR</u>
  - AUGMENTED APERTURE CONCEPT

ONE WAY PILOT BEAM PATH TESTS

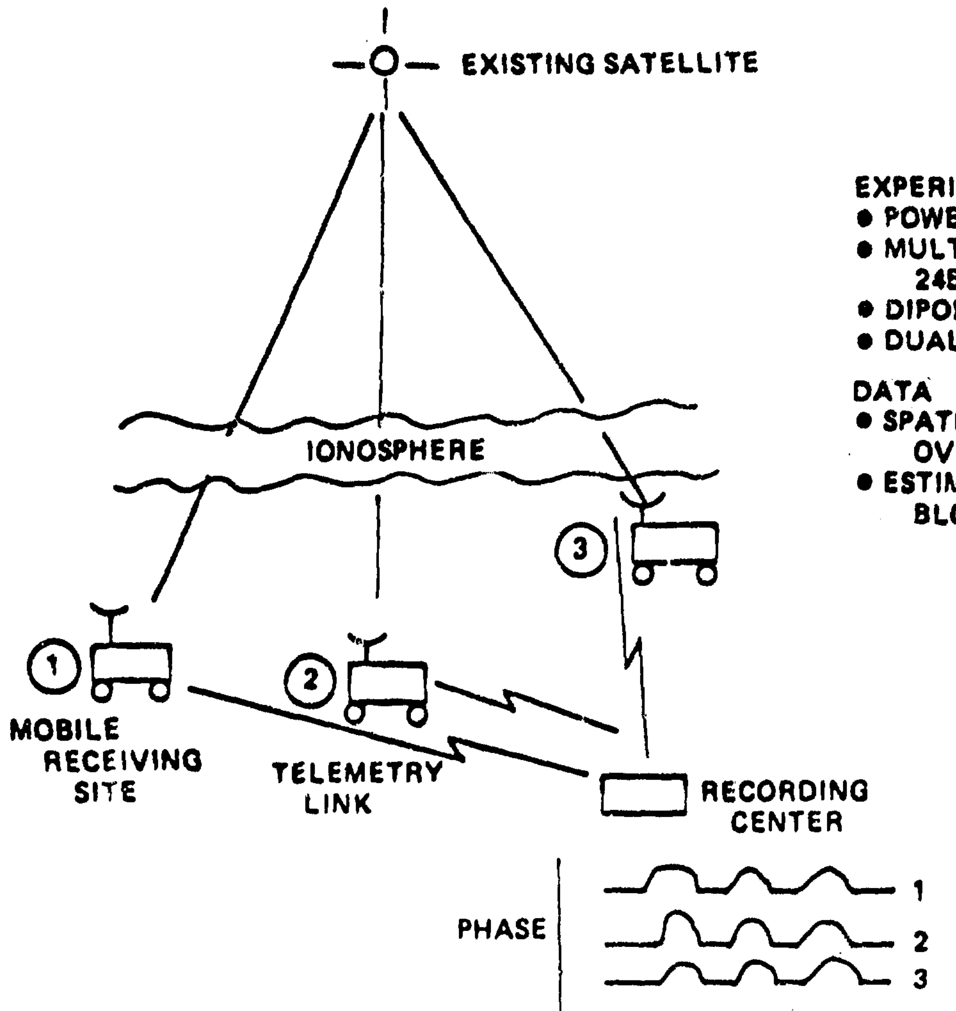
EXPERIMENTAL ASPECTS:

- o POWER LEVEL $<$ 100 WATTS
- o MULTIPLE FREQUENCIES
  2450 $\pm$ 100 MHz BAND
- o DIPOLE TRANSMITTING ANTENNA
- o DUAL POLARIZED RECEIVE ANTENNA

APPLICABILITY OF DATA:

- o SPATIAL & TEMPORAL PHASE FLUCTUATIONS
  OVER SINGLE RAY PATH ONLY
- o ESTIMATE OF IONOSPHERIC COHERENCE
  BLOCK SITE

One Way Pilot Beam Path Test



EXPERIMENT
- POWER LEVEL <100 WATTS
- MULTIPLE FREQUENCIES
  2450 ± 100 MHz BAND
- DIPOLE TRANSMITTING ANTENNA
- DUAL POLARIZED RECEIVE ANTENNA

DATA
- SPATIAL & TEMPORAL PHASE FLUCTUATIONS
  OVER SINGLE RAY PATH ONLY
- ESTIMATE OF IONOSPHERIC COHERENCE
  BLOCK SITE

LARGE APERTURE TECHNOLOGY SATELLITE

EXPERIMENTAL ASPECTS:

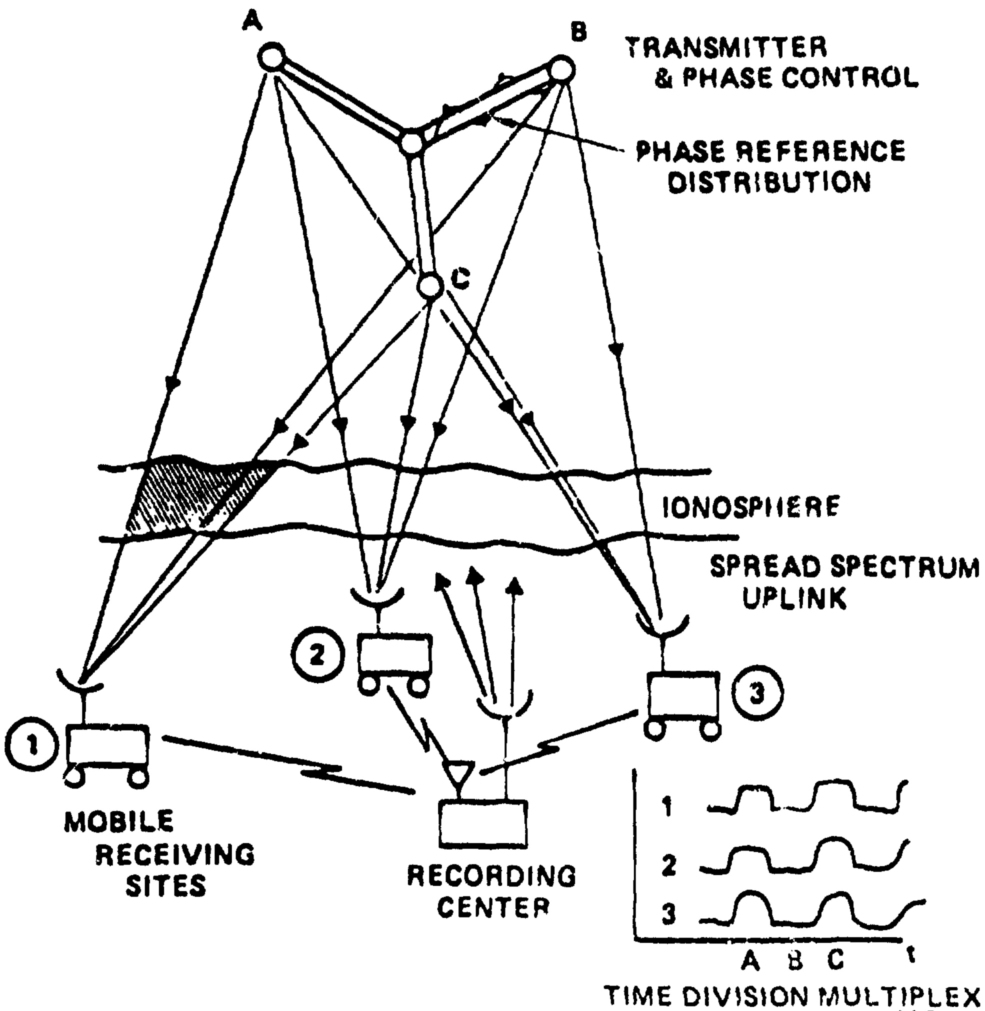
- POWER LEVEL $<$ 100 WATTS PER TRANSMITTER
- ANTENNA
  - LOW GAIN HORN
- FREQUENCY
  - DOWNLINK 2.45 GHz
  - UPLINK: SPREAD SPECTRUM PILOT
- SATELLITE
  - MULTIARM BEAM 600 METER DIA
  - SIZED FOR SINGLE SHUTTLE FLIGHT

APPLICABILITY OF DATA:

- SPATIAL & TEMPARAL FLUCTUATIONS OVER
  SPS IONOSPHERIC BLOCK SIZE
- MODEL MULTILEVEL FULL SCALE PHASE CONTROL
  FOR 3 TO 5 TRANSMITTERS
- DETERMINE RANDOM & SYSTEMATIC PHASE ERRORS
  DUE TO 5-6 METER ION. SECTIONS

Large Aperture Technology Satellite

SPS-2884



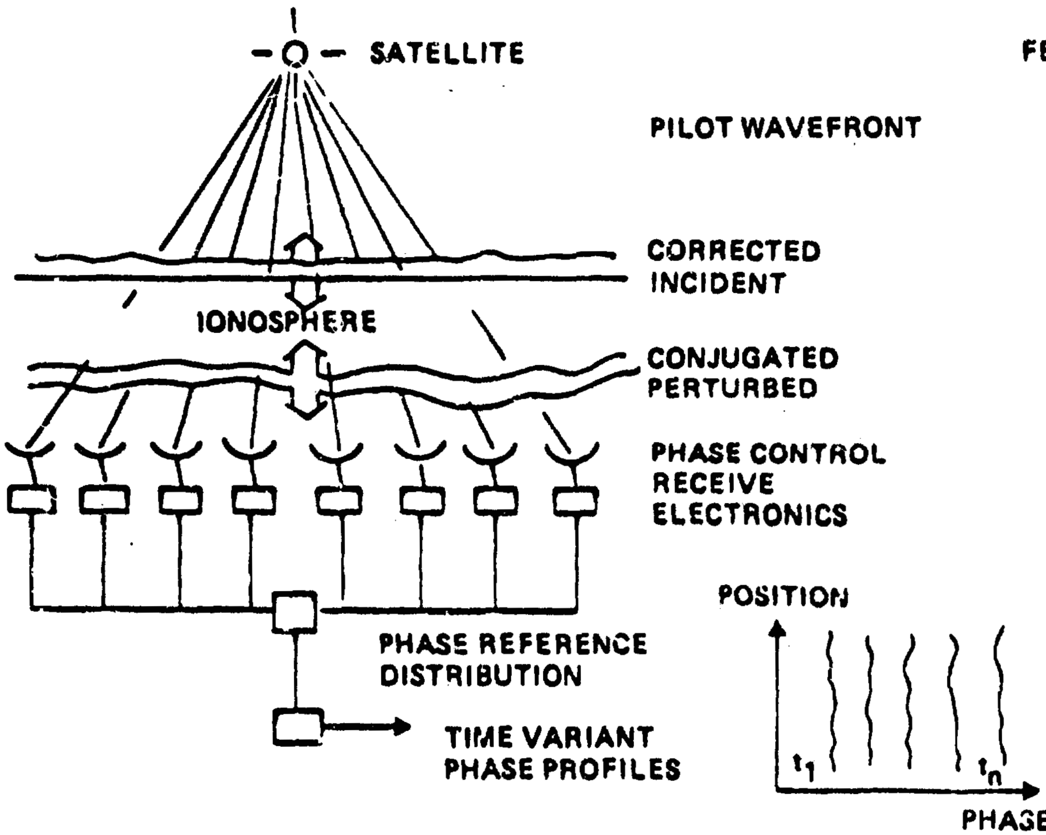
EXPERIMENT
- POWER LEVEL < 100 WATTS PER TRANSMITTER
- ANTENNA
  LOW GAIN HORN
- FREQUENCY
  DOWNLINK 2.45 GHz
  UPLINK: SPREAD SPECTRUM PILOT
- SATELLITE
  MULTIARM BEAM ~ 600 METER DIA
  SIZED FOR SINGLE SHUTTLE FLGIHT

DATA
- SPATIAL & TEMPARAL FLUCTUATIONS OVER SPS IONOSPHERIC BLOCK SIZE
- MODEL MULTILEVEL FULL SCALE PHASE CONTROL FOR 3 TO 5 TRANSMITTERS
- DETERMINE RANDOM & SYSTEMATIC PHASE ERRORS DUE TO 5-8 METER ION. SECTIONS

INVERTED RECEIVE ONLY ARRAY

	FEATURES
	o CAN USE EXISTING SATELLITE
PILOT WAVEFRONT	o PASSIVE–NO SIGNIFICANT POWER
	o CONTINUOUS PHASE FRONT MAPPING FINER GRAIN SPATIAL DETAIL INFINITE NUMBER OF RAYS
CORRECTED INCIDENT PHASE	o POVIDES CHECK OF NEAR FIELD SIMULATION OF DISTORTED WAVEFORM
CONJUGATED PERTURBED PHASE	o PLANAR RECEIVE ONLY 2 DIM. ARRAY WOULD PROVIDE 2D PHASE CONTOUR PPI DISPLAY OBSERVE LARGE SCALE STRIATION IN 2D CORRELATE WITH SCALED HEATING

Inverted Receive Only Line Array



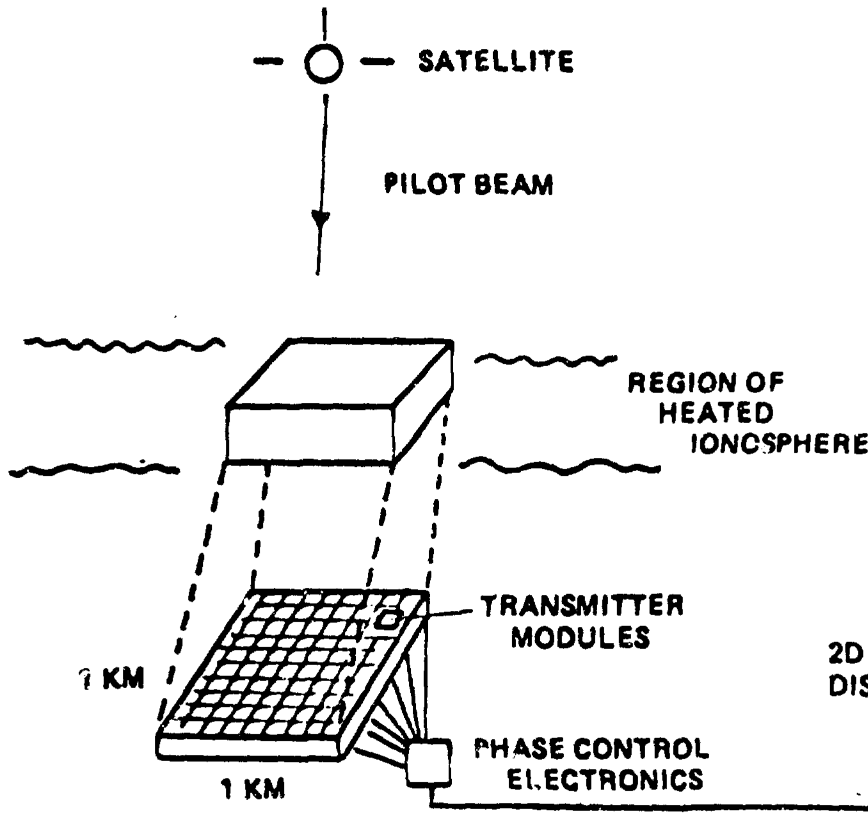
FEATURES

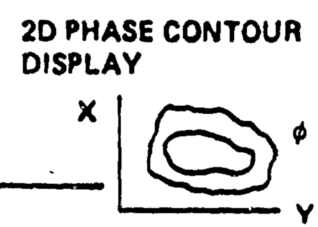
- CAN USE EXISTING SATELLITE
- PASSIVE – NO SIGNIFICANT POWER
- CONTINUOUS PHASE FRONT MAPPING
  - FINER GRAIN SPATIAL DETAIL
  - INFINITE NUMBER OF RAYS
- PROVIDES CHECK OF NEAR FIELD
  - SIMULATION OF DISTORTED WAVEFORM
- PLANAR RECEIVE ONLY 2 DIM. ARRAY WOULD PROVIDE 2D PHASE CONTOUR PPI DISPLAY
  - OBSERVE LARGE SCALE STRIATION IN 2D
  - CORRELATE WITH SCALED HEATING

INVERTED TRANSMIT ARRAY

- TOTAL POWER OF 200 MW
  UNIFORM ILLUMINATION
- PROVIDES 23 MW/CM^2 OVER 1 KM
  IE FULL SCALE HEATING AT S-BAND
- DISPLAYS 2D PLOT OF
  HEATED DISTURBED INOSPHERE
- SPACEBORNE RECEIVER CAN CHECK
  FINE POINTING CAPABILITY
- CHECK UPLINK-DOWNLINK PATH
  DIFFERENCE
- FULL SCALE GROUND THERMAL TEST

Inverted Transmit Array



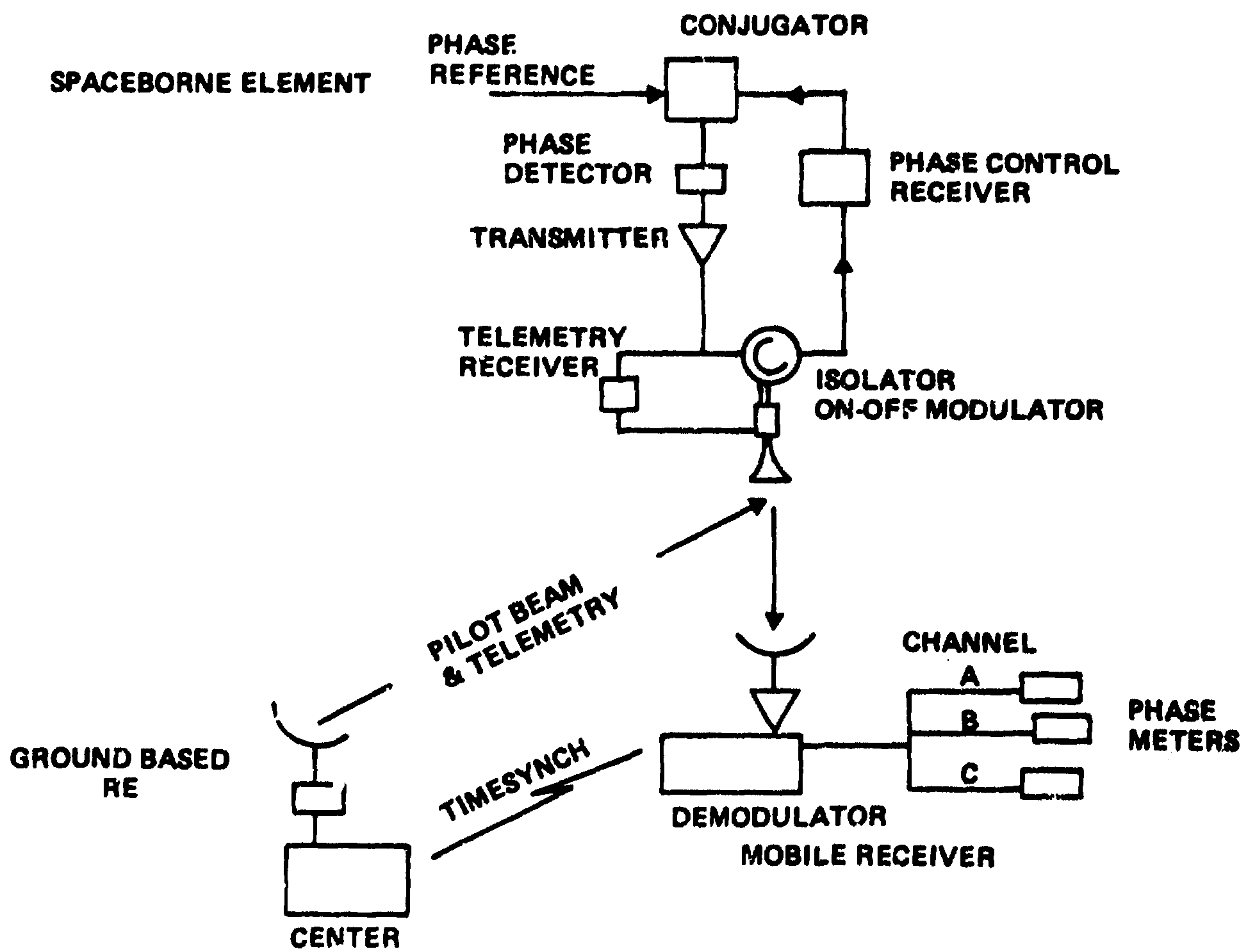


- TOTAL POWER OF 200 MW UNIFORM ILLUMINATION
- PROVIDES 23 MW/CM^2 OVER 1 KM IE FULL SCALE HEATING AT S-BAND
- DISPLAYS 2D PLOT OF HEATED DISTURBED INOSPHERE
- SPACEBORNE RECEIVER CAN CHECK FINE POINTING CAPABILITY
- CHECK UPLINK-DOWNLINK PATH DIFFERENCE
- FULL SCALE GROUND THERMAL TEST

TIME DIVISION MULTIPLEX SYSTEM

Time division multiplexing may allow the ionospheric phase shift from a space-borne transmitter to be determined with less ambiguity and greater ease of implementation than would be the case with an FM CW system. Thus it should be considered for all the phase control system test elements previously described.

Time Division Multiplex System



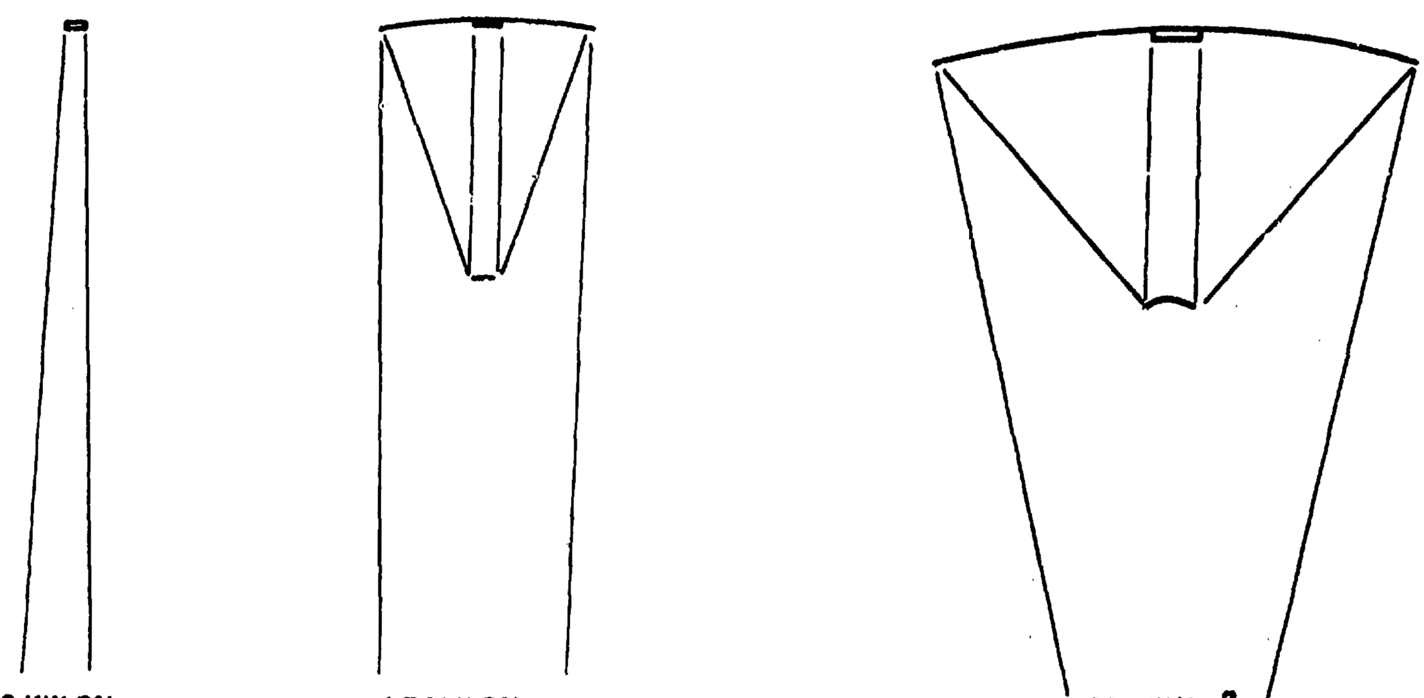
SPS PROGRAM DEMONSTRATOR OPTIONS

It is not yet clear what the SPS demonstrator should be like. Three possible options are shown. Recently, a small trade study of the augmented aperture concept applied to a 16.7 megawatt RF transmitting array was performed. This is the topic of the following section.

SPS Program Demostrator Options

SPACETENNA:

PREVIOUS APPROACH	AUGMENTED APERTURE	ONE TENTH SCALE SPS
100m DIAMETER 16.7 KW RF	1 KM DIAMETER 16.7 MW RF	2.6 KM DIAMENTER 600 MW RF



RECTENNA:

3 KW ON 1 KM x 1 KM	1.7 MW ON 1 KM x 1 KM 14 MW ON 10 KM DIAMETER	23 mW/CM^2 500 MW ON 1.9 KM DIAMETER

AUGMENTED APERTURE STUDY ASSUMPTIONS

In addition to the rather arbitrary 16.7 megawatt power level, the following assumptions were made for the configuration and design of augmented aperture SPS demonstrators.

SPS-2952

Augmented Aperture Study Assumptions

- 100 M DIAMETER ACTIVE ARRAY
- 1 KM DIAMETER APERTURE
- LEO CONSTRUCTION
- ELECTRIC THRUSTERS SELF-POWER TO GEO

APERTURE AUGMENTATION APPROACHES

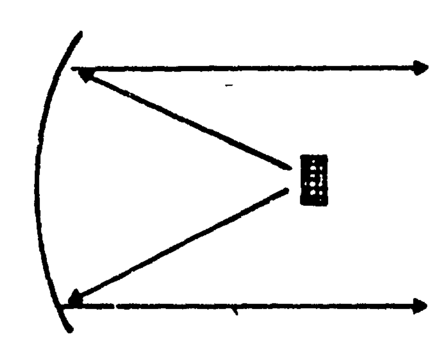
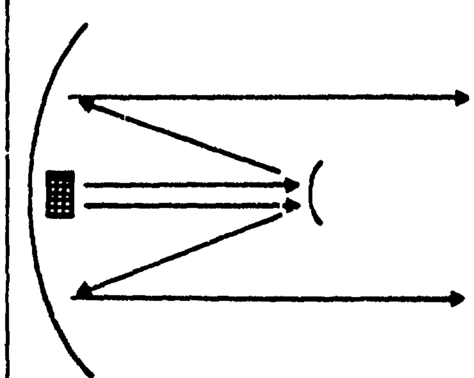
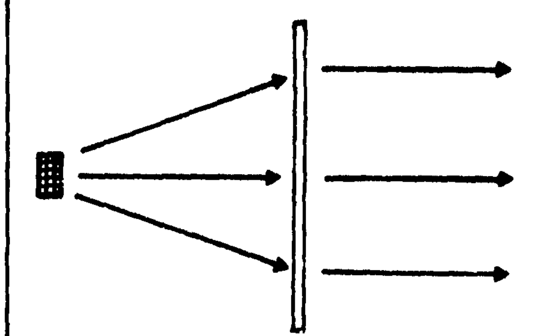
Aperture augmentation approaches may be divided into two basic classes of concepts, using either reflectors or lenses to increase the aperture of the given transmitter array. With the reflectors, a further sub-classification may be made into single and multiple reflector concepts.

Although lenses may be made much more floppy than reflectors and lend themselves to active control, they also have significant power loss as the beam passes through them. Although this may not be crucial for an SPS demonstrator, it was felt to be sufficient to exclude the lenses from our present consideration. They should perhaps be reintroduced later.

Aperture Augmentation Approaches

SPS-2960

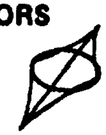
BOEING

REFLECTOR		LENS
		
• SURFACE MUST STAY WITHIN 10^{-5} OF MAJOR DIMENSION	• REQUIRE EITHER LOW COEFF OF EXPANSION MATLS OR ACTIVE CONTROL	(ARRAYS OF PHASE SHIFTERS) • ALLOW $10-10^2$ MORE FIGURE DEFORMATION THAN REFLECTORS • NO BLOCKAGE AT APERTURE CENTER • LEND THEMSELVES TO ACTIVE CONTROL • EFFICIENCY?
a) SINGLE REFLECTOR • LENDS ITSELF TO HIGH F–NUMBER GRAVITY GRADIENT ASSISTED CONFIGURATION	b) DUAL REFLECTORS • LOWEST MOMENTS BEST FOR ARBITRARY POINTING • SOMEWHAT MORE COMPLEX OPTICS	

ACTIVE REFLECTOR CONCEPTS FOR APERTURE AUGMENTATION

Preliminary study showed that passive reflectors that would hold their figure were unattractive when compared with simple actively controlled reflectors. Of the types of actively controlled reflectors that might be envisioned and that were feasible with the current shuttle, the two most attractive ones were the maypole and hoop multiple flight deployed flexible reflectors and the faceted and modular constructed flexible reflectors. While the maypole and hoop concept may be the least massive per unit area, the faceted modular concept appears to be the most constructable.

Active Reflector Concepts For Aperture Augmentation

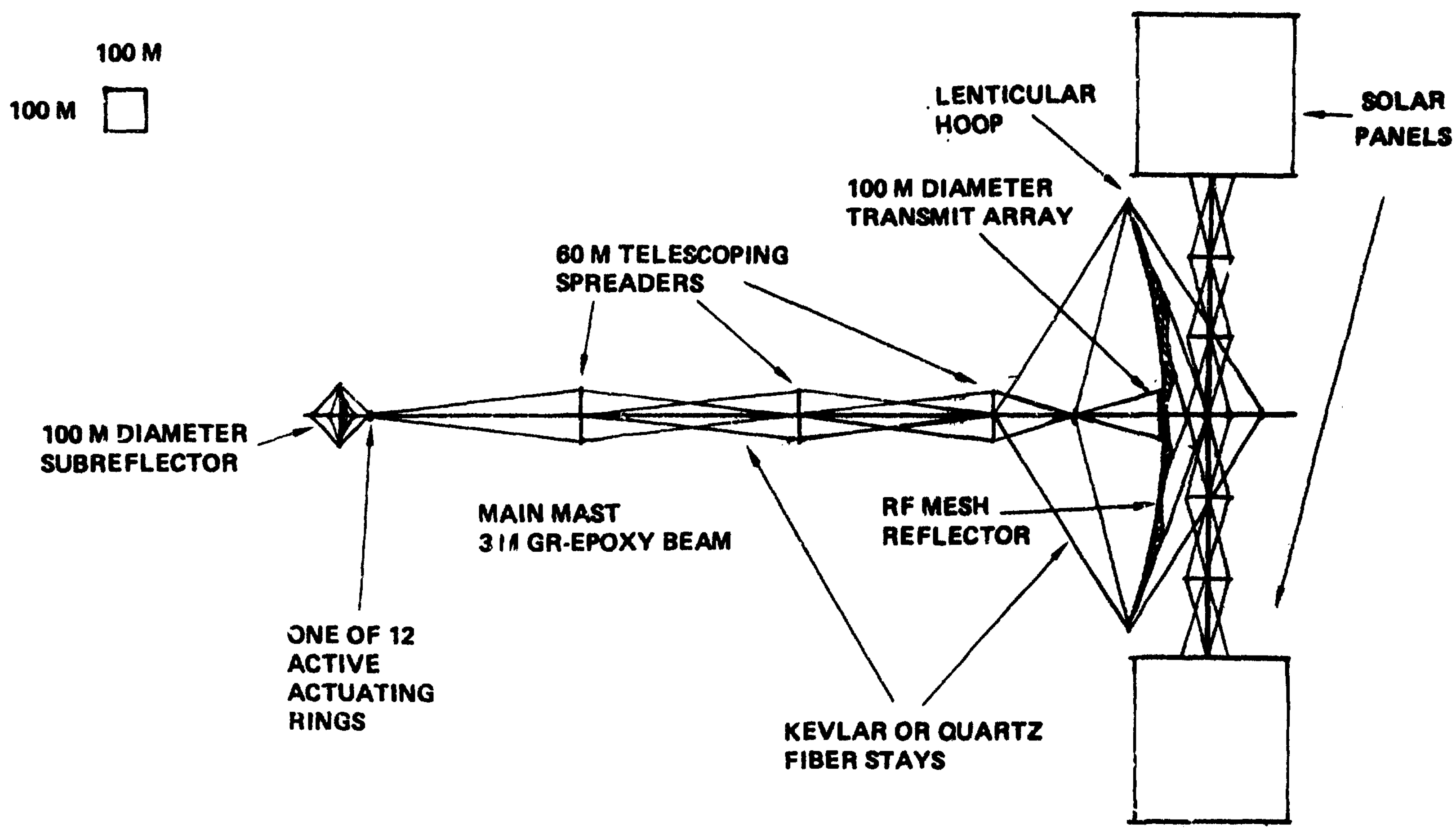
• DEPLOYED RIGID SURFACE REFLECTORS		>1 KG M^{-2}, TOO MASSIVE AND COSTLY
• SINGLE-FLIGHT DEPLOYED FLEXIBLE REFLECTORS		MAY BE FEASIBLE WITH 125 KLB SHUTTLE
• MULTI-FLIGHT DEPLOYED FLEXIBLE REFLECTORS		FEASIBLE WITH CURRENT SHUTTLE
• MAYPOLE AND HOOP		$<.1$ KG M^{-2} EASILY SCALED UP
• RIBS		RIB TOLERANCES AND MASSES ARE A PROBLEM SCALING UP A PROBLEM
• FACETED/MODULAR		MORE MASSIVE THAN MAYPOLE AND HOOP EASILY SCALED UP
• CONSTRUCTED RIGID SURFACE REFLECTORS		>1 KG M^{-2}
• CONSTRUCTED FLEXIBLE REFLECTORS		DIFFICULT TO BUILD ALIGNMENT SLOW
• MAYPOLE AND HOOP		LINE TANGLING PROBLEM POTENTIAL LEAST CONSTRUCTABLE
• RIBS		RIBS VERY CONSTRUCTABLE, MESH PROBLEMATIC
• FACETED/MODULAR		MOST CONSTRUCTABLE RELATIVELY MASSIVE

CASSEGRAIN REFLECTOR AUGMENTED APERTURE

A design for cassegrain reflector augmented aperture SPS demonstrator using two maypole hoop reflectors was configured and is as shown. The shape of the entire structure is controlled by adjusting tensions of selected lines from active actuating rings. These rings are centers for the act of control of the satellite. Basic stiffness of the masts that position the elements of the satellite and the reflector surfaces is provided by stays under tension. The reflectors are somewhat analogous to bicycle wheels, while the mast technology was drawn from masts on high performance sailboats which use diamonds and spreaders.

BOEING SPS

Cassegrain Reflector Augmented Aperture

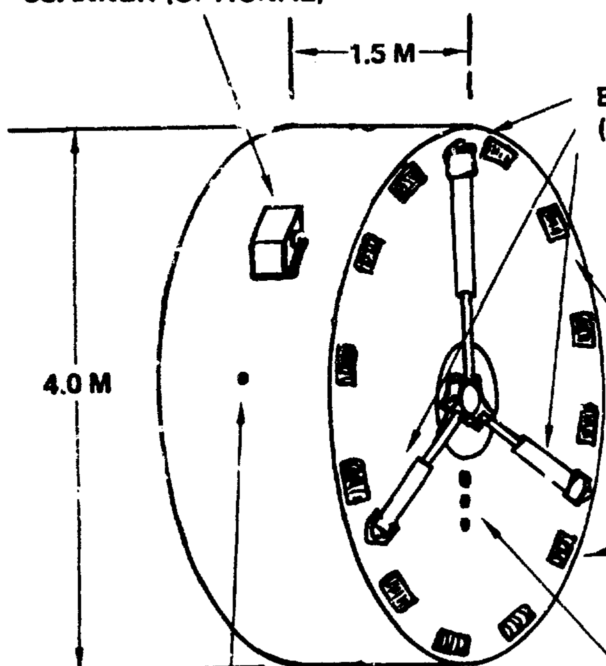


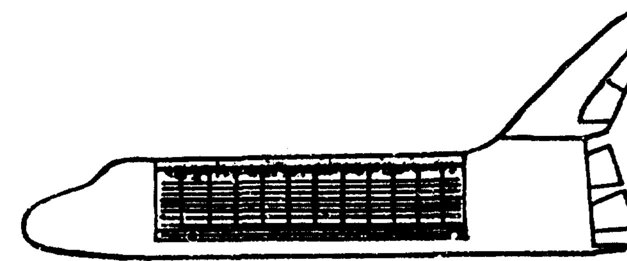
ACTIVE ACTUATING RING UNIT

It was found that an active actuating ring unit design may be quite compact; enough so that all twelve rings with the spreaders that are deployed from them and the mesh from the main reflector could conceivably fit into the shuttle for single flight.

BOEING SPS

Active Actuating Ring Unit





PRELIMINARY CASSEGRAIN MASS STATEMENT

Using mass properties scaled from existing Lockheed and Harris maypole hoop reflector designs, it was found that the additional mass to augment the aperture of the 16.7 megawatt SPS demonstrator was a less than 50% increase.

Preliminary Cassegrain Mass Statement

ITEM	MASS (MT)	COMMENTS
SOLAR ARRAY	76	
100 M DIAMETER TRANSMIT ARRAY	130	
BASIC DEMONSTRATOR SUBTOTAL	206	
3 M BEAM FOR MASTS	14.4	4 KG/M
ACTIVE RINGS	3.6	300 KG EACH
60 M TELESCOPING SPREADERS	3.0	1 KG/M
STAYS	.6	
MAIN REFLECTOR HOOP	1.5	
MAIN REFLECTOR MESH	1.1	
SHAPING NET	2.0	
SUBREFLECTOR	2.0	
MISC	10.0	
AUGMENTATION SUBTOTAL	37.2	
SUM	243.2	
20% GROWTH	48.6	
TOTAL	291.8	

APERTURE AUGMENTATION CONSTRUCTION SCENARIO

A rather conservative scenario was developed for the construction of the cassegrain type aperture augmented satellite for SPS demonstration.

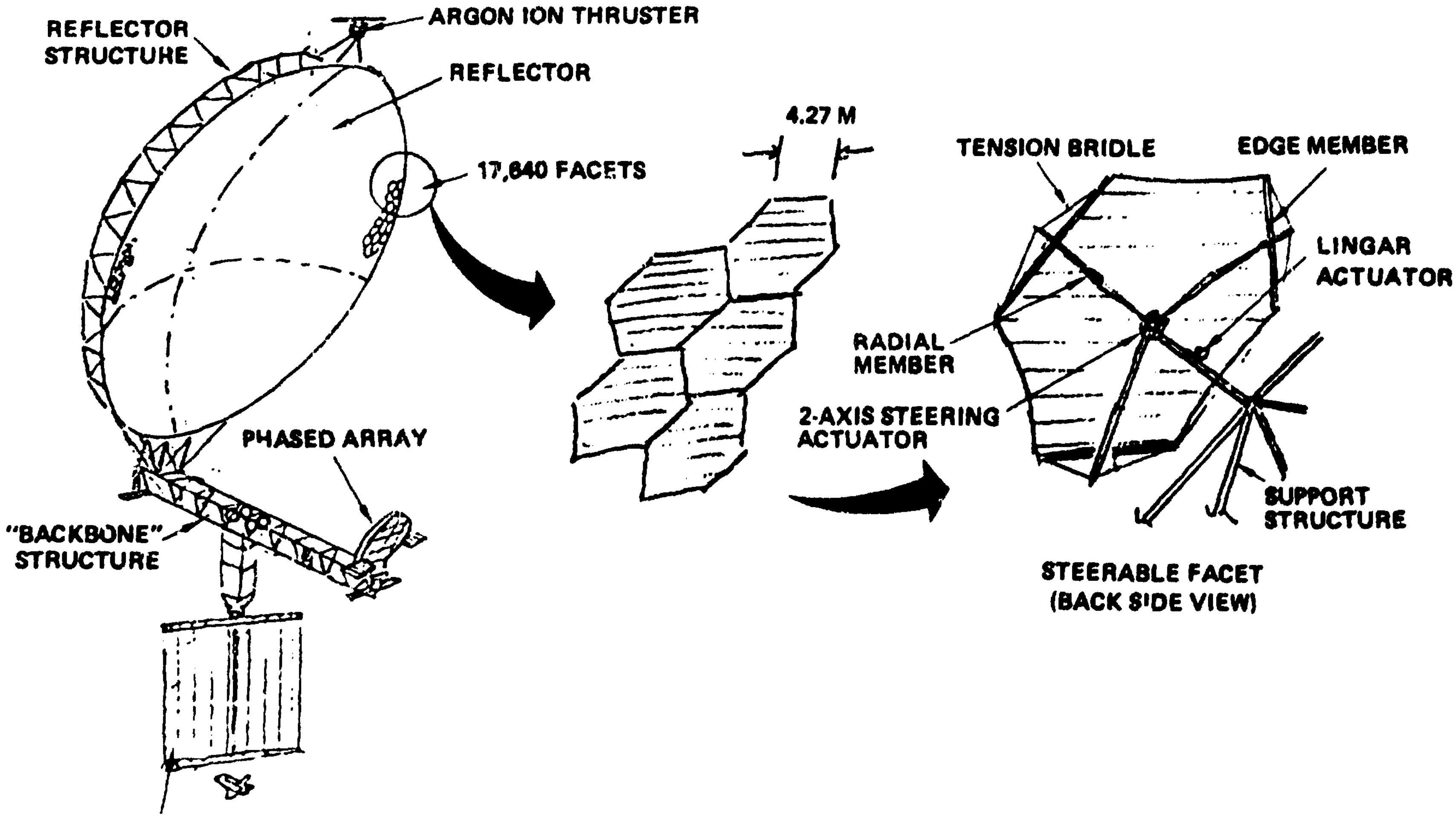
Aperture Augmentation Construction Scenario

OPERATION	TIME
• ASSEMBLE TRANSMITTING ARRAY	200 DAYS
• DEPLOY MAST FROM TRANSMITTING ARRAY (ADDING RINGS PERIODICALLY)	7 DAYS
• DEPLOY SOLAR ARRAYS	50 DAYS
• DEPLOY HOOP AND	
• FLY MAST THROUGH	2 DAYS
• CONNECT 6 STAYS TO SECURE HOOP POSITION ABOUT MAST	
• ADD REMAINING MAIN REFLECTOR STAYS	20 DAYS
• UNFOLD REFLECTING MESH	5 DAYS
• ATTACH SHAPING NET	30 DAYS
• ALIGN AND PERFORM FINAL CHECKOUT	60 DAYS
• FLY TO GEO, THRUSTING ALONG MAST AXIS	120-180 DAYS

ALTERNATIVE DEPLOYABLE TRUSS FACETED REFLECTOR

An alternative aperture augmented satellite design with a somewhat more conservative structural design was developed. It consists of a rigid reflector structure supporting steerable facets much like those on a thermal SPS with the exception of the inclusion of a linear actuator to provide in-out positioning of the reflector facet. The size of the deployable facets was determined by the length of the shuttle bay. The grating lobes that would be induced by the discontinuities between the facets were calculated and found not to be excessive.

Alternative Deployable Truss Faceted Reflector

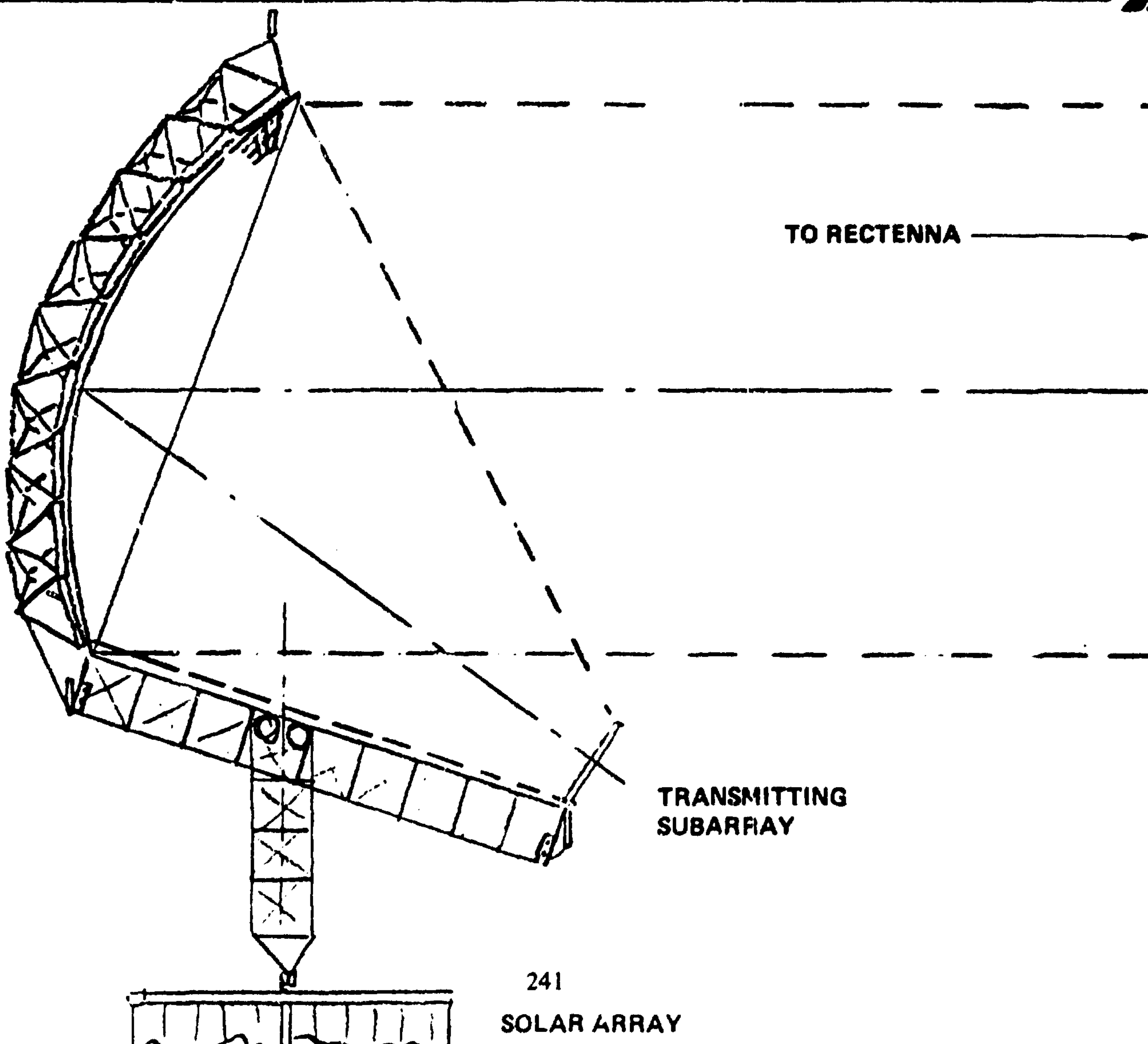


STEERABLE FACET (BACK SIDE VIEW)

TRUSS/FACET CONFIGURATION OFFSET OPTICS

The optics for the alternative deployable truss faceted reflector SPS augmented aperture demonstrator configuration are shown. The fact that the transmitting subarray is out of the main beam is attractive both from an antenna pattern and maintenance during operation viewpoint. There is a necessary satellite center of gravity and moment of inertia asymmetry but it should not result in excessive attitude control system requirements.

Truss/Facet Configuration Offset Optics



TRUSS/FACET CONFIGURATION MASS STATEMENT

A mass statement for the truss facet aperture augmentation SPS demonstrator configuration shows that this alternative is much more massive, mostly due to the high mass of the structure in it.

Truss/Facet Configuration Mass Statement

ITEM	MASS (METRIC TONS)	
TRANSMITTING ARRAY	130	
SOLAR ARRAY	76	
REFLECTOR	434	
PRIMARY STRUCTURE		66
SECONDARY STRUCTURE		274
STEERABLE FACETS		94
BACKBONE STRUCTURE	40	
MISCELLANEOUS	20	
SUM	700	
20% GROWTH	147	
TOTAL	847	

TRUSS/FACET ALTERNATIVE CONSTRUCTION SCENARIO

Due to the greater mass and complexity of the elements to be assembled construction of the truss/facet alternative satellite takes longer than that of the cassegrain configuration. Again, this construction scenario is probably somewhat conservative.

Truss/Facet Alternative Construction Scenario

ASSEMBLE TRANSMITTING ARRAY	200 DAYS
ASSEMBLE BACKBONE	50 DAYS
DEPLOY SOLAR ARRAY	50 DAYS
ASSEMBLE REFLECTOR TRUSS STRUCTURE	200 DAYS
DEPLOY FACETS	20 DAYS
FINAL CHECKOUT	60 DAYS

PRELIMARY APERTURE AUGMENTATION IMPACT SUMMARY

Facts about the 16 megawatt SPS demonstrator without aperture augmentation and two aperture augmented alternatives are listed. The bottom line of total costs shows that for between 1.4 and 2 times as much money, one may increase transmitting aperture by a factor of 100 and received power on a demonstration rectenna by over 500 to the power level of a small utility.

SPS

Preliminary Aperture Augmentation Impact Summary

BOEING

SPS-2986

PARAMETER	16 MW DEMO	16 MW DEMO WITH CASSEGRAIN MAYPOLE-HOOP REFLECTOR	Δ CASSEGRAIN	16 MW DEMO WITH DEPLOYABLE TRUSS FACETED REFLECTOR	Δ TRUSS FACETED
TRANSMITTING APERTURE	7854 m^2	777540 m^2	x 99	785400 m^2	x 100
RECEIVED POWER (1 KM x 1 KM RECTENNA)	3 kw	1.73 Mw	x576	1.8 Mw	x 600
CONSTRUCTION TIME	310 DAYS	374 DAYS	x1.2	580 DAYS	x1.9
MASS	250 MT	300 MT	x1.2	847 MT	x3.4
SHUTTLE FLIGHTS	20	27	x1.35	56	x2.8
HARDWARE	14	18	x1.3	44	x3.1
CONS BASE	6	9	x1.5	12	x2.0
DDT&E COST	$1.67 B	$2.67 B	x1.6	$2.17 B	x1.3
HARDWARE COST	$0.16 B	$0.26 B	x1.6	$0.26 B	x1.6
CONSTRUCTION BASE COST	$1.70 B	$2.55 B	x1.5	$3.40 B	x2.0
SELF POWER TRANSFER COST	$0.30 B	$0.40 B	x1.3	$1.00 B	x3.3
GSO SUPPORT STATION COST	$0.50 B	$0.50 B	NO CHANGE	$0.50 B	NO CHANGE
EARTH-LEO TRANSPORT COSTS					
FLIGHT	$0.40 B	$0.54 B	x1.35	$1.12 B	x2.8
FLEET	$0.20 B	$0.27 B	x1.35	$0.56 B	x2.8
CHEMICAL OTV COST	$0.20 B	$0.20 B	NO CHANGE	$0.20 B	NO CHANGE
CREW ROTATION COSTS	$0.08 B	$0.10 B	x1.2	$0.16 B	x2.0
RECTENNA COST	$0.15 B	$0.15 B	NO CHANGE	$0.15 B	NO CHANGE
17.5% FOR OPERATIONS	$0.94 B	$1.35 B	x1.4	$1.71 B	x1.8
TOTAL COSTS	$6.30 B	$8.99 B	x1.4	$11.23 B	x1.8

CONSTRUCTION SIMILARITIES WITH FULL SCALE SPS

Due to its unique design the cassegrain configuration has only partial similarity with a baseline SPS in several respects. This is not true for the truss/facet configuration which incorporates technology throughout that has basically full similarity with SPS baseline designs as we know them today.

Construction Similarities with Full Scale SPS

ASPECT	CASSEGRAIN CONFIGURATION		TRUSS/FACET CONFIGURATION	
	PARTIAL SIMILARITY	FULL SIMILARITY	PARTIAL SIMILARITY	FULL SIMILARITY
AUTOMATIC BEAM ASSEMBLY	X			X
COMPOSITE MATERIALS		X		X
REPRESENTATIVE SIZES	X			X
REPRESENTATIVE TOLERANCES	X			X

COMMENTS ON APERTURE AUGMENTATION

The big advantage of aperture augmentation is that it allows the power beam parameters to be scaled closer to full scale and the test rectenna output to be closer to utility scale without the investment in mass and cost that would be required for a full scale SPS. The cost would essentially be doubled and the additional technology effort would be partially applicable to a full scale SPS.

Further trade studies to be done on aperture augmented SPS demonstrators are listed. Particularly important is the increase in satellite power which may be done with only marginal cost growth in the demonstrator.

Comments on Aperture Augmentation

SPS-2979

- SPS DEMONSTRATOR APPLICABILITY
  - ALLOWS POWER BEAM PARAMETERS TO BE CLOSE TO FULL SCALE WITHOUT BUILDING FULL SCALE SATELLITE
  - ADDITIONAL TECHNOLOGY EFFORT PARTIALLY APPLICABLE TO FULL SCALE SPS
  - 1.5 – 2x PRECURSOR COST ALLOWS FULL SCALE SPS BEAM EFFICIENCIES
  - UTILITY SCALE POWER OUTPUT

- FURTHER TRADE STUDIES TO DO ON APERTURE AUGMENTATION
  - INCREASE SATELLITE POWER (MARGINAL COST GROWTH)
  - REFLECTORS VS LENSES
  - MULTIPLE ELEMENT OPTICS FOR HIGH POWER (> 20 GW) SPS
  - MECHANICAL VS ELECTROSTATIC ACTUATORS FOR REFLECTORS
  - MORE DETAILED COSTS AND MASSES

MPTS TEST PLAN OPTIONS

Aspects of various program options in the microwave power transmission system test plan for SPS are shown in a matrix.

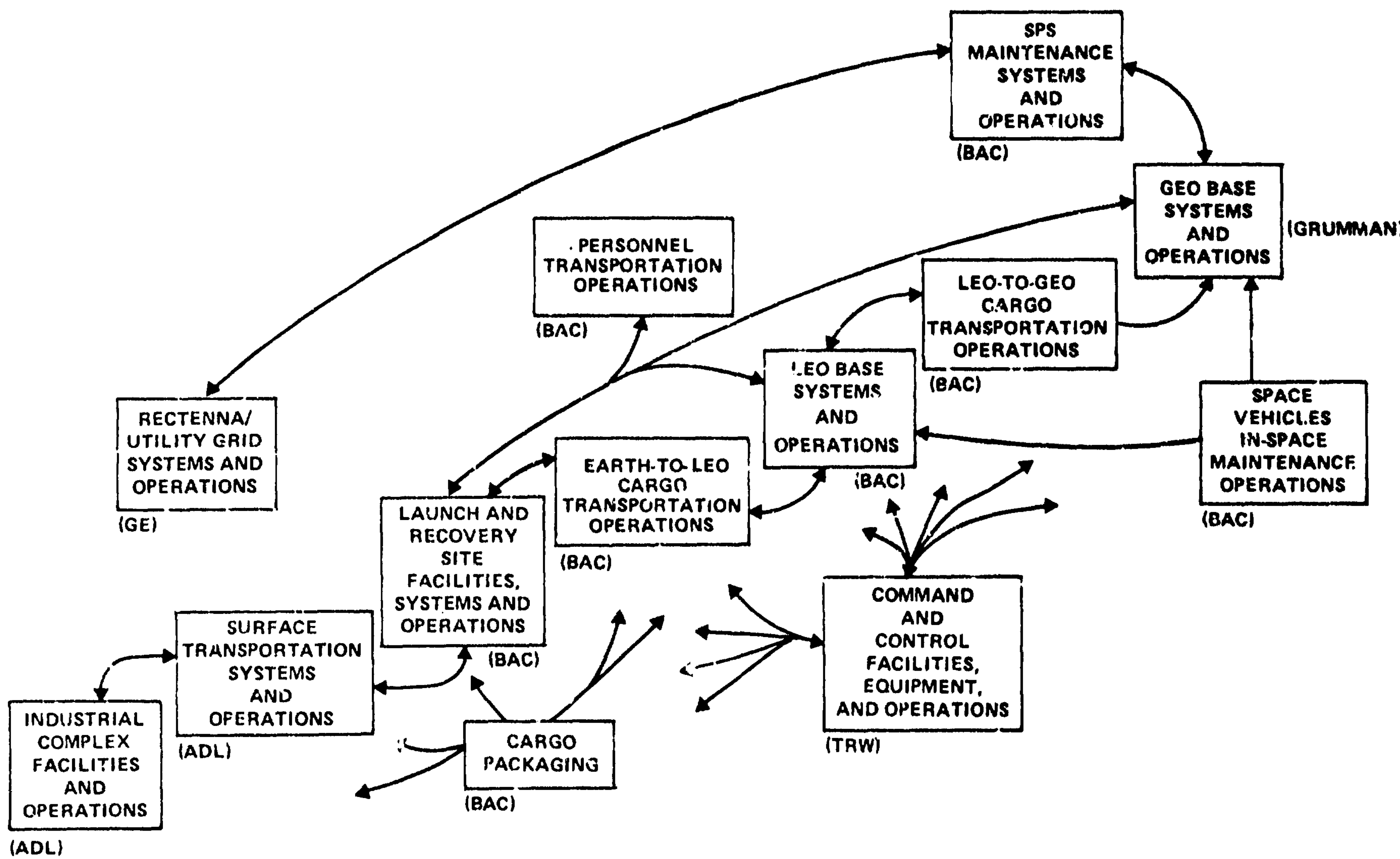
The one way path experiments could be done immediately with existing satellites. They provide limited but perhaps adequate information about the ionosphere for further SPS development. The LAPATS satellite would provide more extensive ionospheric information as well as phase control system concept feasibility information. The inverted arrays supplement this and, if they are planar and transmit power, provide crucial high power beam phase control system information. With proper design inverted arrays and LAPATS could be used together.

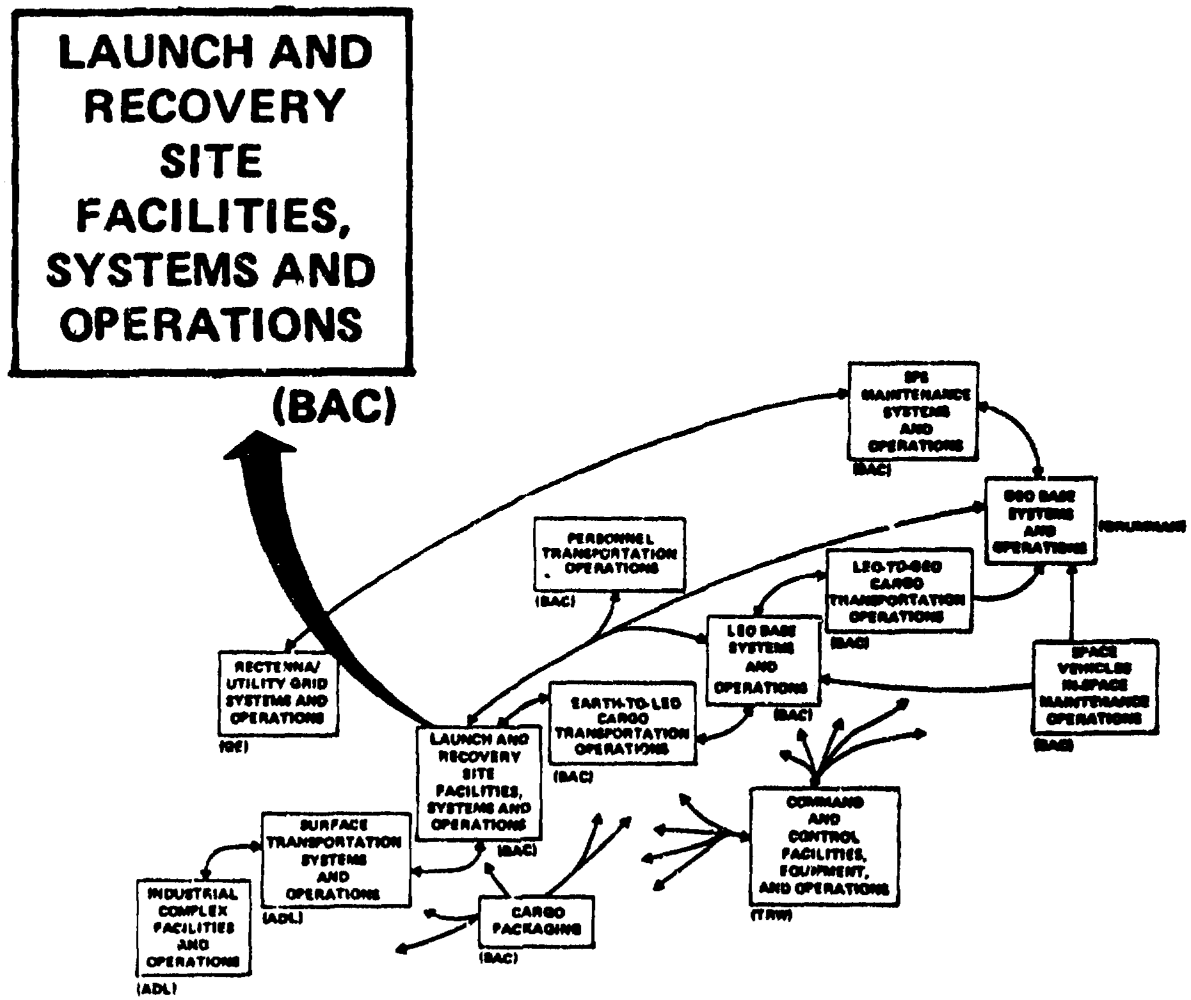
Of the SPS demonstrators, it appears that around 500 megawatts is necessary to adequately demonstrate full scale SPS technology. To a certain extent this may be reduced by the use of aperture augmentation. Further study is needed to quantify this reduction.

MPTS Test Plan Options

	ONE-WAY PATH		LAPATS		INVERTED LINEAR		INVERTED PLANAR			LEO-LEO	GEO-GROUND	SPS
	SINGLE SITE	MULTI SITE	SINGLE SITE	MULTI SITE	REC. ONLY	TRANS MIT	REC. ONLY	300M 2 MW	1 KM 200 MW	200 KW	500 MW	5 GW
MICROWAVE POWER AMPLIFIER												
LOW POWER								●	●			
FULL POWER										●	●	●
THERMAL										●	●	●
SOLID STATE LOW POWER												
HIGH POWER												
TRANSMITTING ARRAY											●	●
SPACE FABRICATION										●	●	●
POWER HANDLING										●	●	●
THERMAL EFFECTS												
PHASE CONTROL												
IN SPACE ENVIRONMENT			●	●							●	●
IN SPACE & THERMAL ENVIRONMENT											●	●
PHASE REF. DISTRIBUTION			●	●	●	●	●	●	●		●	●
CONJUGATION			●	●	●	●	●	●	●		●	●
TUBE LOOP								●	●		●	●
IONOSPHERE												
TIME, FREQ. & POLAR. MEAS.												
SINGLE RAY PATH	●		●									
MULTIPLE RAY PATH		●		●								
1-D PROFILE					●	●						
2-D MAP							●	●	●			
HEATING COLD	●	●	●	●	●		●					
SCALED 1/12					●	●						
SPS @ 2.45 GHZ								●	●		●	●
RECTENNA										●	●	●
HIGH EFFICIENCY POWER TRANSFER										●	●	●

Phase II Systems and Operations Studies



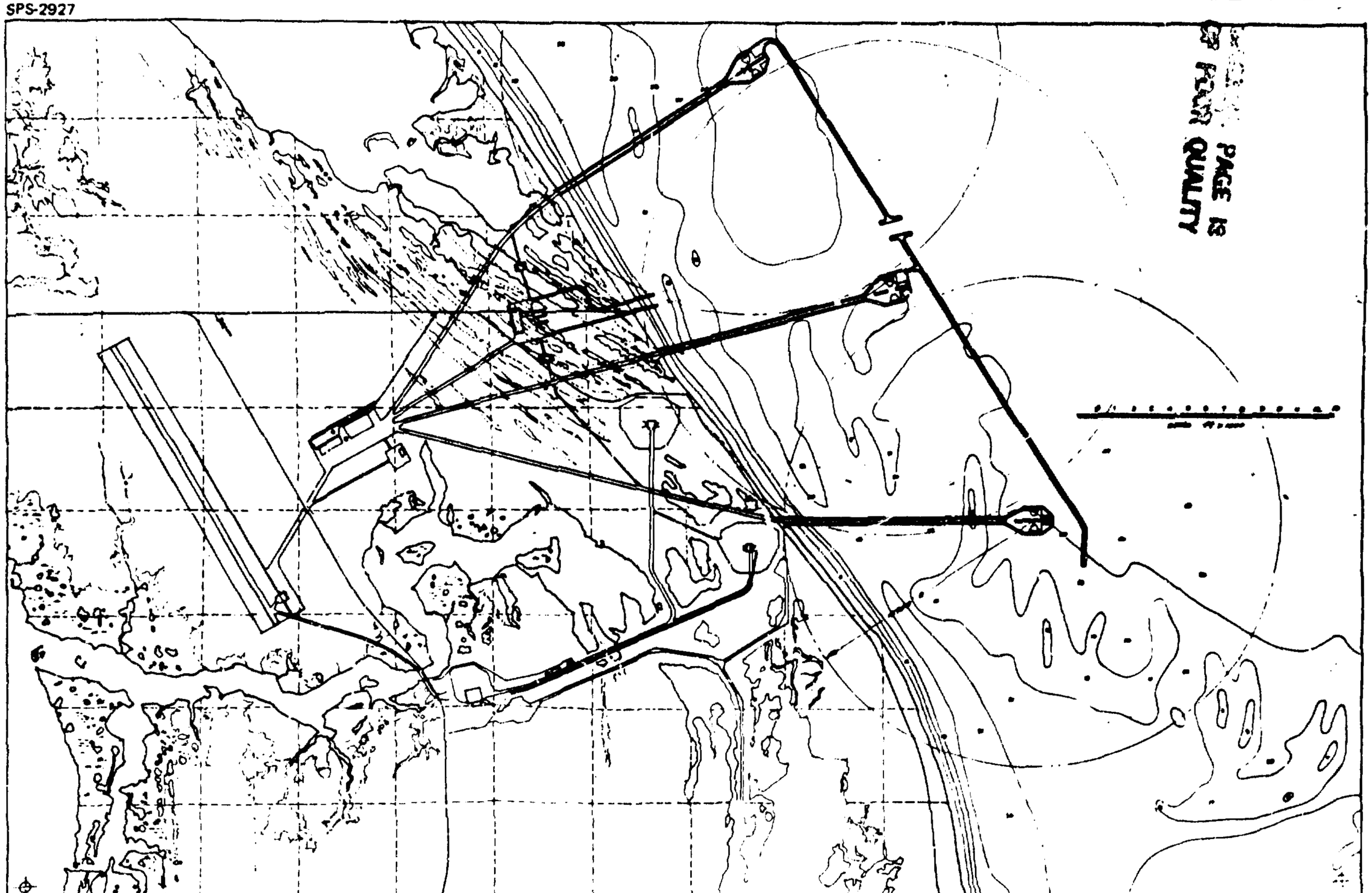

LAUNCH AND RECOVERY SITE FACILITIES, SYSTEMS AND OPERATIONS
(BAC)
SPS MAINTENANCE SYSTEMS AND OPERATIONS
(BAC)
GEO BASE SYSTEMS AND OPERATIONS
PERSONNEL TRANSPORTATION OPERATIONS
(BAC)
LEO-TO-GEO CARGO TRANSPORTATION OPERATIONS
(BAC)
LEO BASE SYSTEMS AND OPERATIONS
(BAC)
SPACE VEHICLES IN-SPACE MAINTENANCE OPERATIONS
RECTENNA/ UTILITY GRID SYSTEMS AND OPERATIONS
(GE)
EARTH-TO-LEO CARGO TRANSPORTATION OPERATIONS
(BAC)
LAUNCH AND RECOVERY SITE FACILITIES, SYSTEMS AND OPERATIONS
(BAC)
COMMAND AND CONTROL FACILITIES, EQUIPMENT, AND OPERATIONS
(TRW)
SURFACE TRANSPORTATION SYSTEMS AND OPERATIONS
(ADL)
INDUSTRIAL COMPLEX FACILITIES AND OPERATIONS
(ADL)
CARGO PACKAGING
(BAC)

OVERLAY OF SPS FACILITIES ON KSC MAP

The Kennedy Space Center is the reference location of the SPS Launch and Recovery Site. Other locations have not been ruled out. This map shows the reference location of the SPS facilities at KSC.

Overlay of HLLV Pads on KSC Map

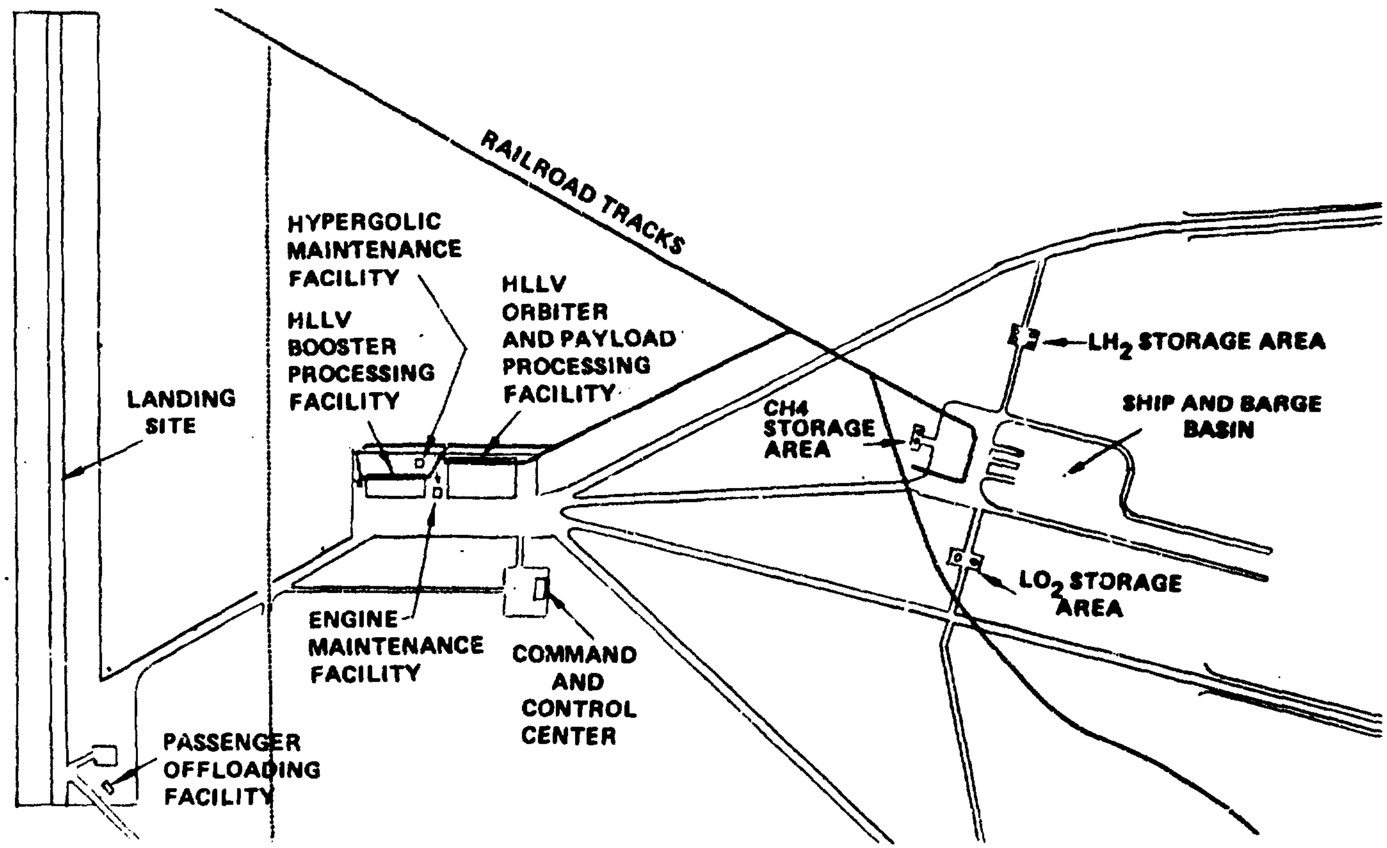
SPS-2927



SPS GROUND SUPPORT FACILITIES

This map shows a close-up view of some of the HLLV facilities. Two of these facilities will be described in subsequent charts.

SPS Ground Support Facilities

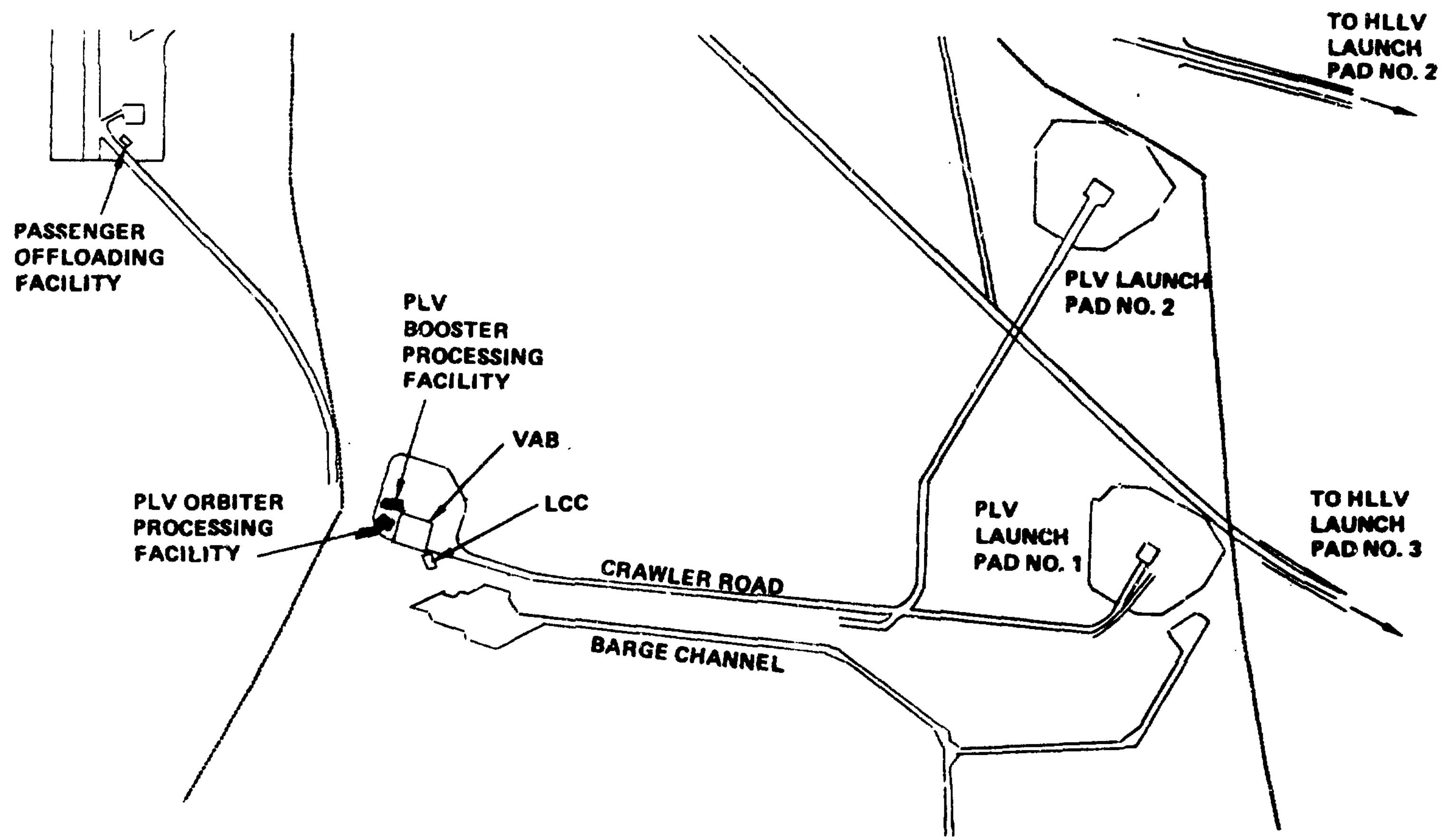


SPS GROUND SUPPORT FACILITIES SHARED WITH THE SPACE TRANSPORTATION SYSTEM

This map shows a close-up view of some of the PLV facilities. The PLV is considered to be a Shuttle-Growth vehicle, so its processing facilities will be those developed for the Shuttle-Growth vehicle. The PLV vehicle processing will be integrated with the processing of other Shuttle-Growth vehicles assigned to other missions.

SPS Ground Support Facilities Shared With the Space Transportation System

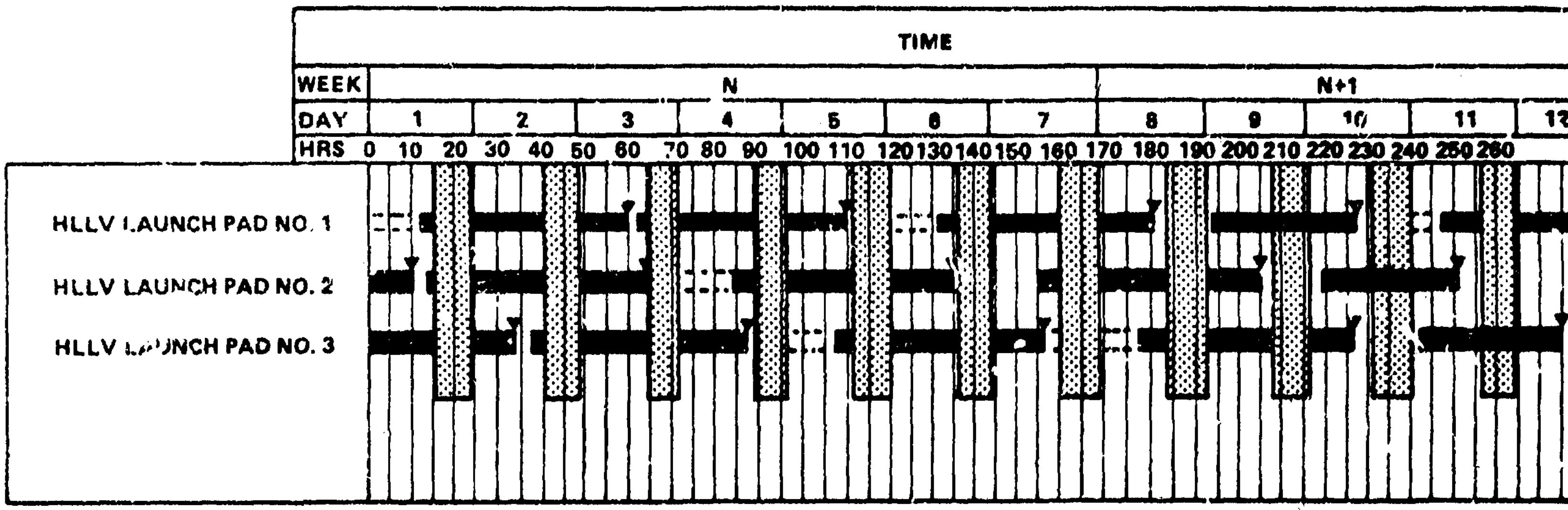
SPS-2926



HLLV LAUNCH PAD OPERATIONS

This figure illustrates the integrated operational timelines for the three HLLV launch pads. This timeline is based on launching 400 HLLV's per year. A 7-day/week 2-shifts/day schedule is the preferred schedule. Other schedules, such as 5-days/week 2 shifts and 5-days/week 3 shifts were also considered. The selected schedule provides for the most efficient use of the launch pads (minimal slack time) while allowing sufficient time available (the 8-hour/day shutdown) to make up lost time. This available time could also be utilized to support a higher launch rate or to keep the space construction on schedule if one of the three launch pads become inoperative (for example, because of a vehicle explosion on the pad).

HLLV Launch Pad Operations



TIMELINE PARAMETERS
- 7 DAY/WEEK, 2 SHIFTS
- 34 HRS PAD OPS TIME
- 11 HR FINAL BLOCK TIME
- 8 LAUNCHES/WEEK (400 LAUNCHES/YR)

KEY
- LAUNCH PAD OPERATIONS
- SLACK TIME
- NIGHTLY SHUTDOWN

OBSERVATIONS
- HAVE TO WORK THRU THE NIGHT EVERY OTHER WEEK
- HAVE TO SHIFT THE SHIFT SCHEDULE TO ADAPT TO SLIDING LAUNCH OPPORTUNITY TIME

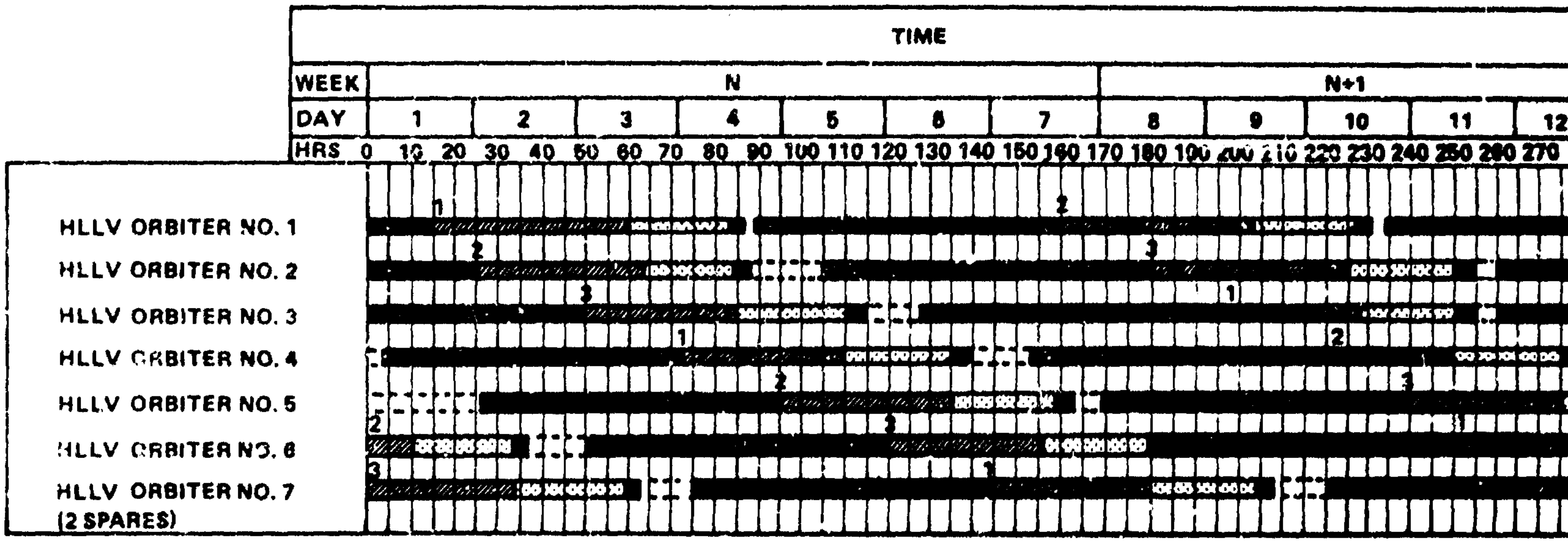
HLLV ORBITER PROCESSING OPERATIONS

This figure shows the integrated processing operations for seven HLLV Orbiters.

It was found that a 7-day/week, 3-shifts/day schedule was the most efficient schedule as well as leading to a requirement for fewer orbiters than would be required by other schedules. The selected schedule was based on 400 launches per year. As this timeline shows, only four of the five bays would be occupied at any time. The additional bay would be used to perform major overhauls that would require the vehicle to be removed from the operational cycle.

HLLV Orbiter Processing Operations

SPS-2905



TIMELINE PARAMETERS

- 7 DAYS/WEEK, 3 SHIFTS SYNCHRONIZED TO 7 DAY/WEEK, 2 SHIFT LAUNCH PAD SCHEDULE
- 97 HR ORBITER PROCESSING TIME WITH MINIMUM 27 HR BLOCK TIME AFTER LAUNCH
- 8 LAUNCHES/WEEK (400 LAUNCHES/YEAR)

KEY

- HLLV ORBITER PROCESSING FACILITY ACTIVITY
- HLLV LAUNCH PAD NO. 1 ACTIVITY
- HLLV FLIGHT AND ORBITAL ACTIVITY
- SLACK TIME

HLLV ORBITER AND PAYLOAD PROCESSING FACILITY

This figure illustrates the configuration of the HLLV Orbiter and Payload Processing Facility.

The HLLV Orbiters are backed into one of the bays. Access platforms are moved into place and the vehicle is connected to facility power and other services. The cargo bay is opened and the empty cargo pallet removed. The vehicle is then processed to prepare it for its next launch.

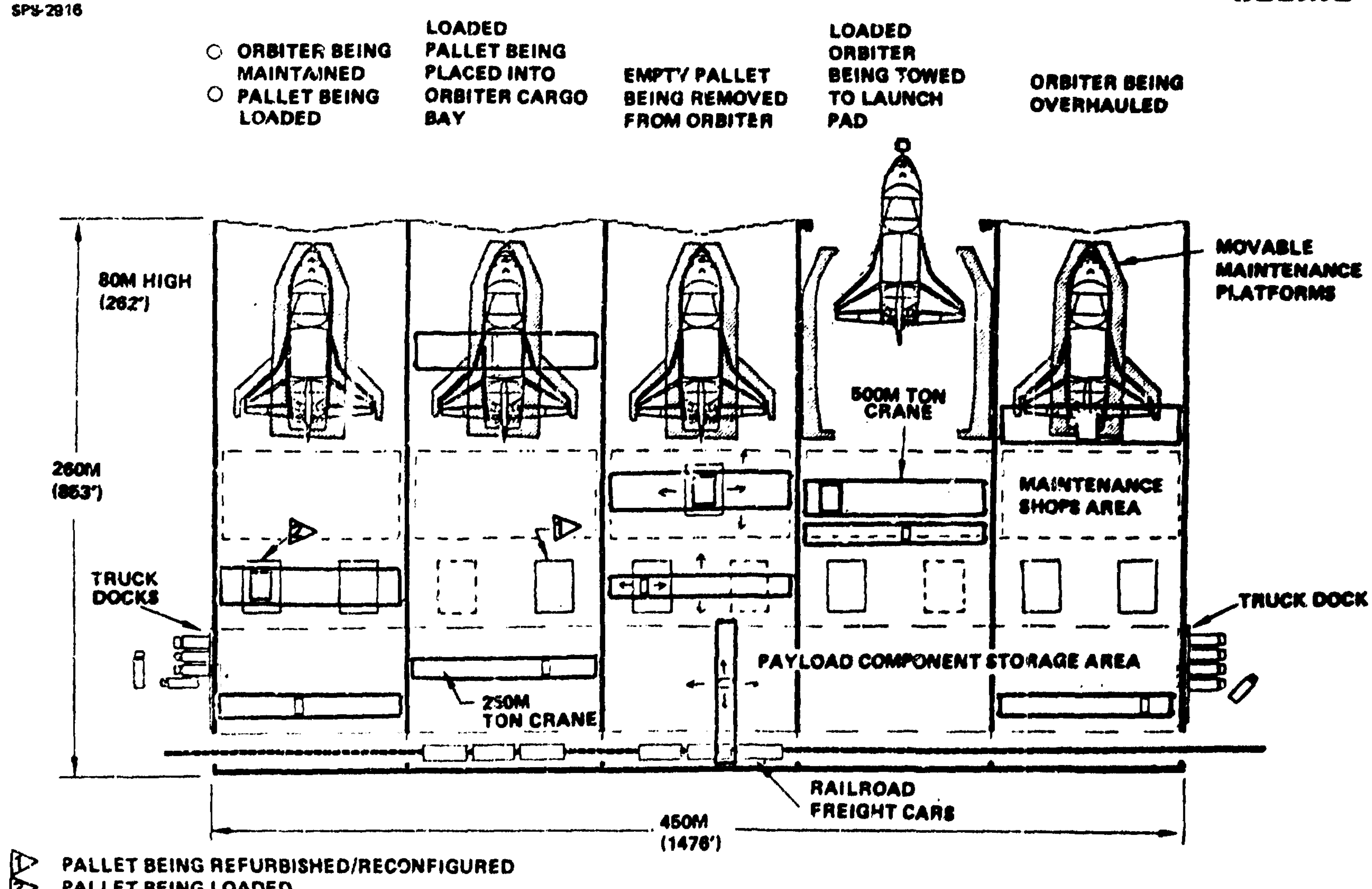
The empty pallet is taken to a processing location where it is then reconfigured for its next payload.

The components are delivered to the facility by truck and/or rail. These components are distributed to the appropriate bays. The components are moved to the pallet loading area where the pallet is filled with the goods called for by a shipping manifest.

One of the bays will always be available for vehicles undergoing major maintenance.

HLLV Orbiter and Payload Processing Facility

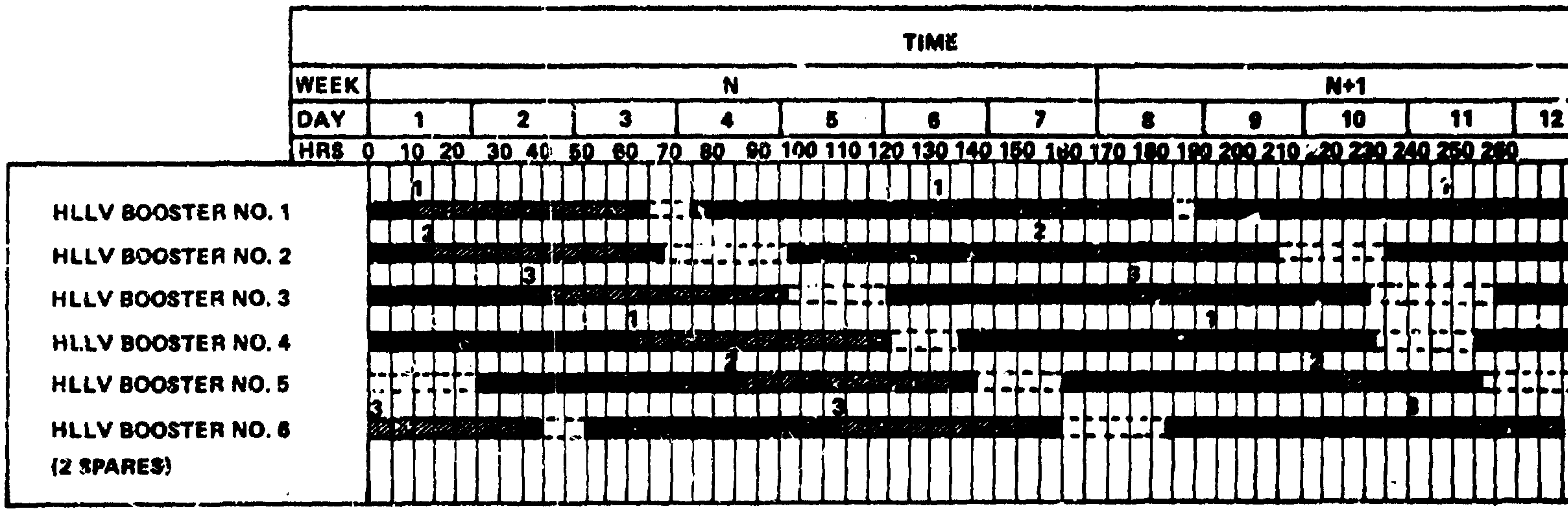
SPS-2916



HLLV BOOSTER PROCESSING OPERATIONS

This figure illustrates the integrated operational timeline for the processing of six HLLV Boosters. Three of the vehicles will be on launch pads and three will be in the processing facility at any one time.

HLLV Booster Processing Operations



TIMELINE PARAMETERS
- 7 DAYS/WEEK, 3 SHIFTS
- SYNCHRONIZED TO 7 DAY/WEEK, 2 SHIFT LAUNCH PAD SCHEDULE
- 62 HR BOOSTER PROCESSING TIME, 4 HR [illegible] BLOCK TIME AT BEGINNING OF EACH
- 8 LAUNCHES/WEEK

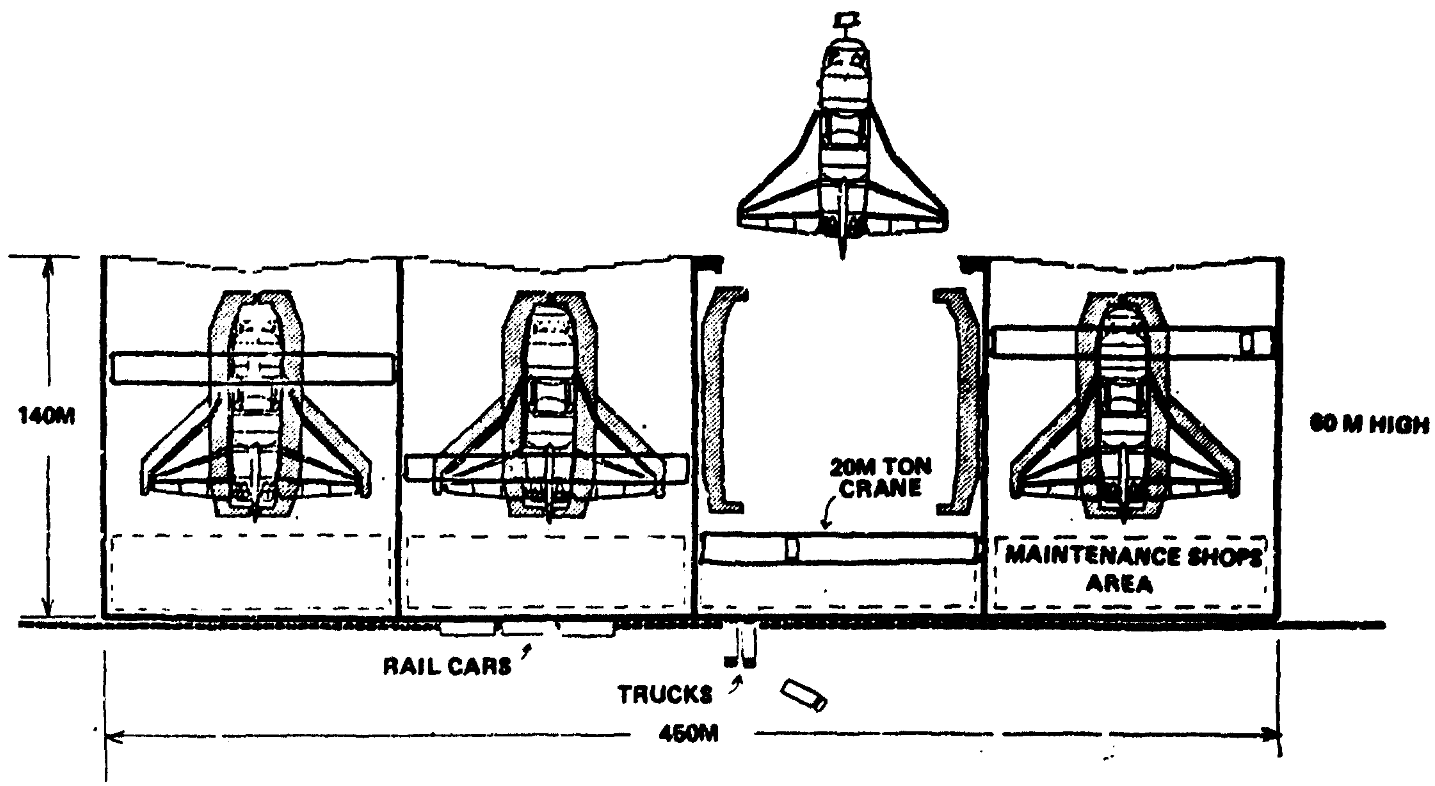
KEY

- HLLV BOOSTER PROCESSING FACILITY ACTIVITY
- HLLV LAUNCH PAD NO. 1 ACTIVITY
- SLACK TIME

HLLV BOOSTER PROCESSING FACILITY

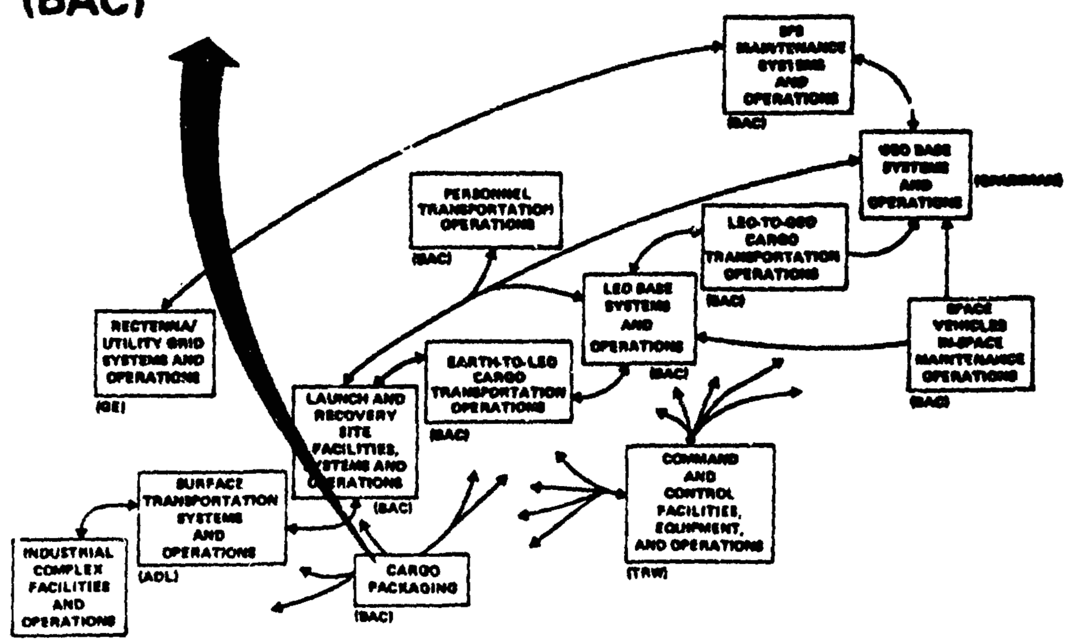
This figure illustrates the configuration of the HLLV Booster Processing Facility. Three of the bays will have operational vehicles in the turnaround cycle. The other bay will be available for extended-duration major maintenance.

HLLV Booster Processing Facility



CARGO PACKAGING

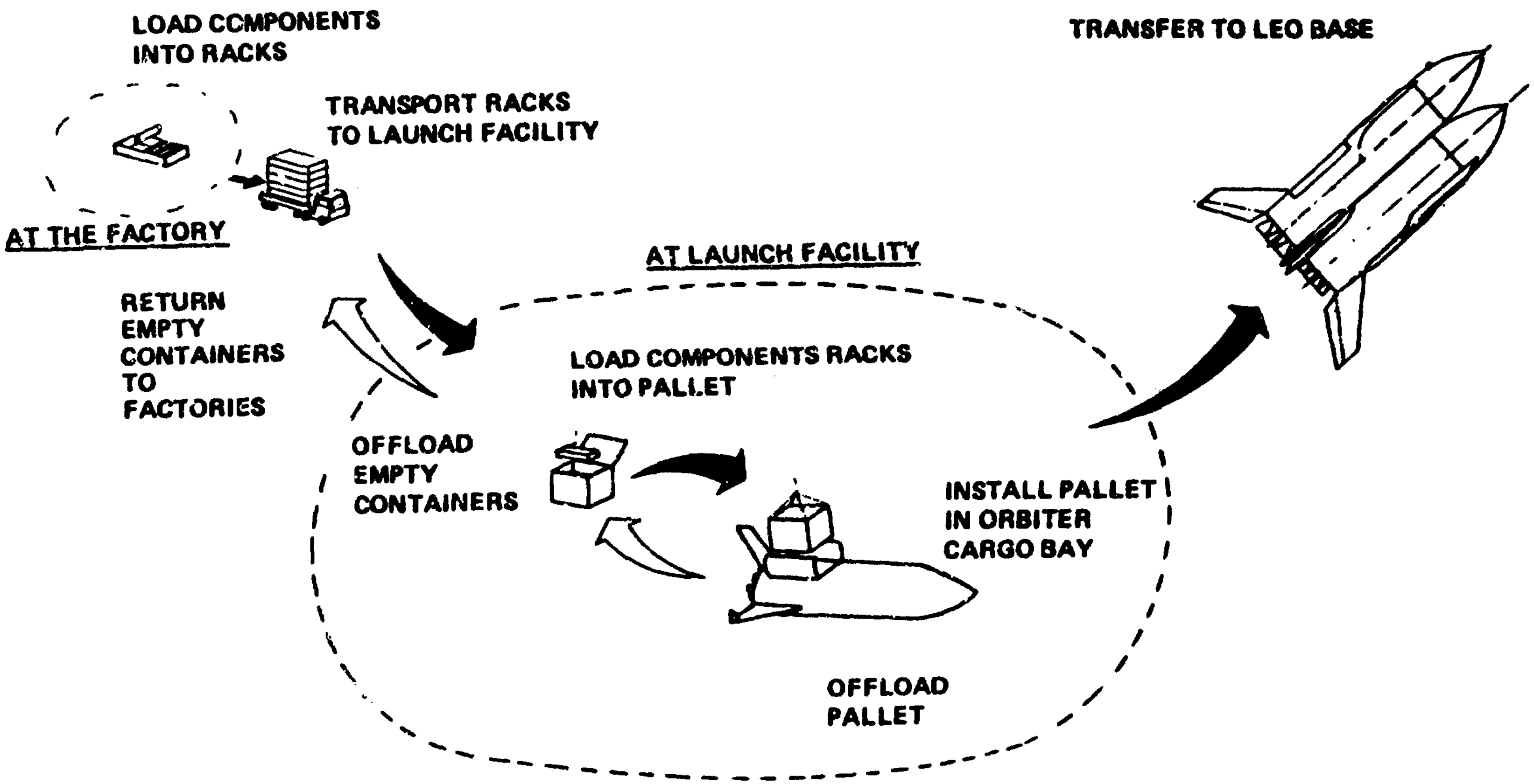
(BAC)



CARGO HANDLING OPERATIONAL FLOW CYCLE (ON-EARTH)

The on-Earth cargo handling operational flow cycle is illustrated in the figure. The components are initially loaded into component magazines and racks at the various factories. These magazines and racks are transported to the Launch and Recovery Site where they are temporarily stored. A shipping manifest is prepared and the various component magazines and racks are then taken from storage. The components are integrated into cargo pallets. The cargo pallets are then loaded into an HLLV orbiter.

Cargo Handling Operational Flow Cycle

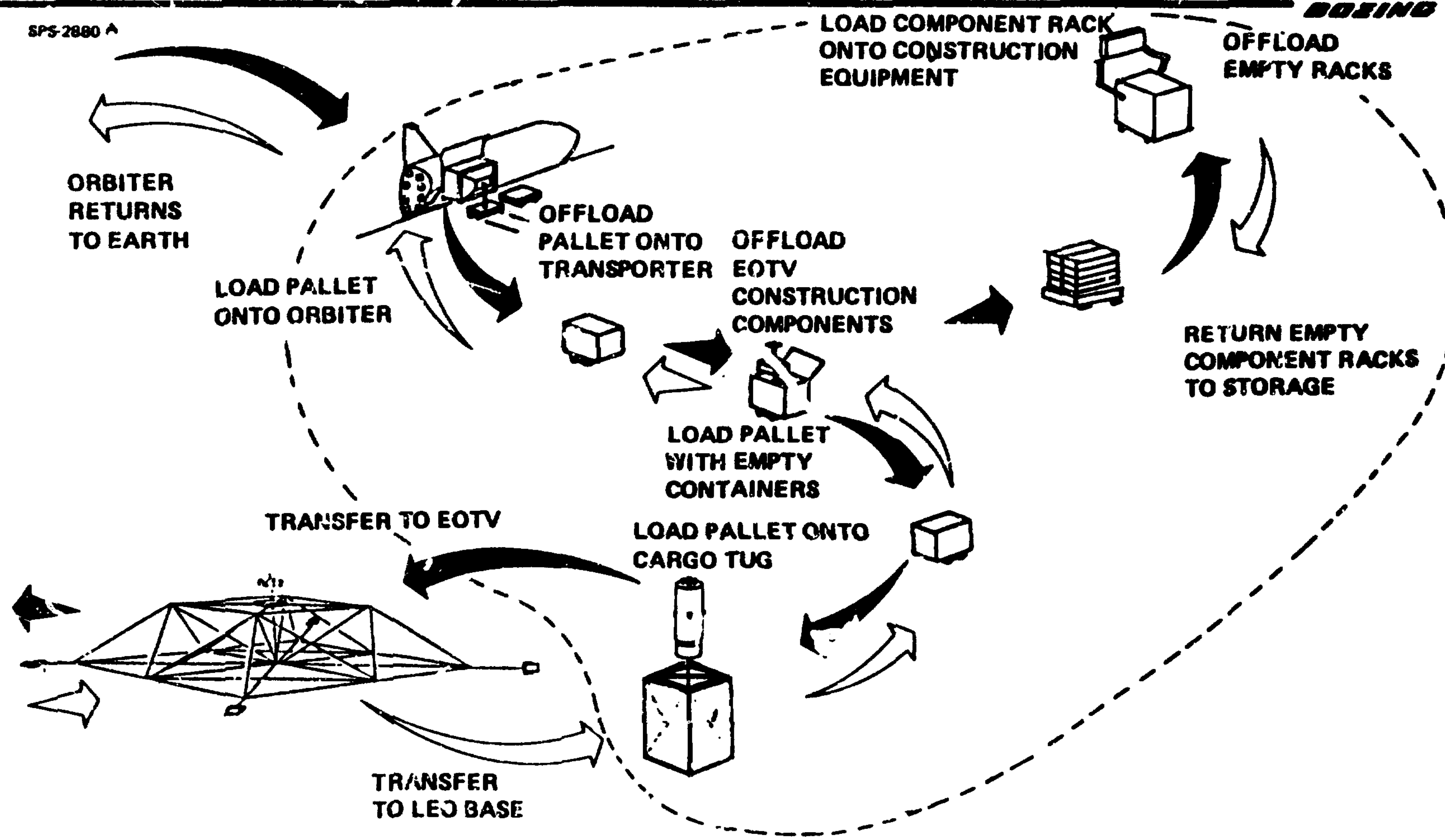


CARGO HANDLING OPERATIONAL FLOW CYCLE (AT LEO BASE)

At the LEO Base, the cargo pallet is removed from the HLLV and is transported to a cargo handling and storage area. The EOTV components destined for use at the LEO Base are removed from the pallets. The SPS pallets are transported to the EOTV using cargo tugs. Ten to twenty of the pallets are attached to the EOTV cargo platform.

Cargo Handling Operational Flow Cycle

SPS-2880 A



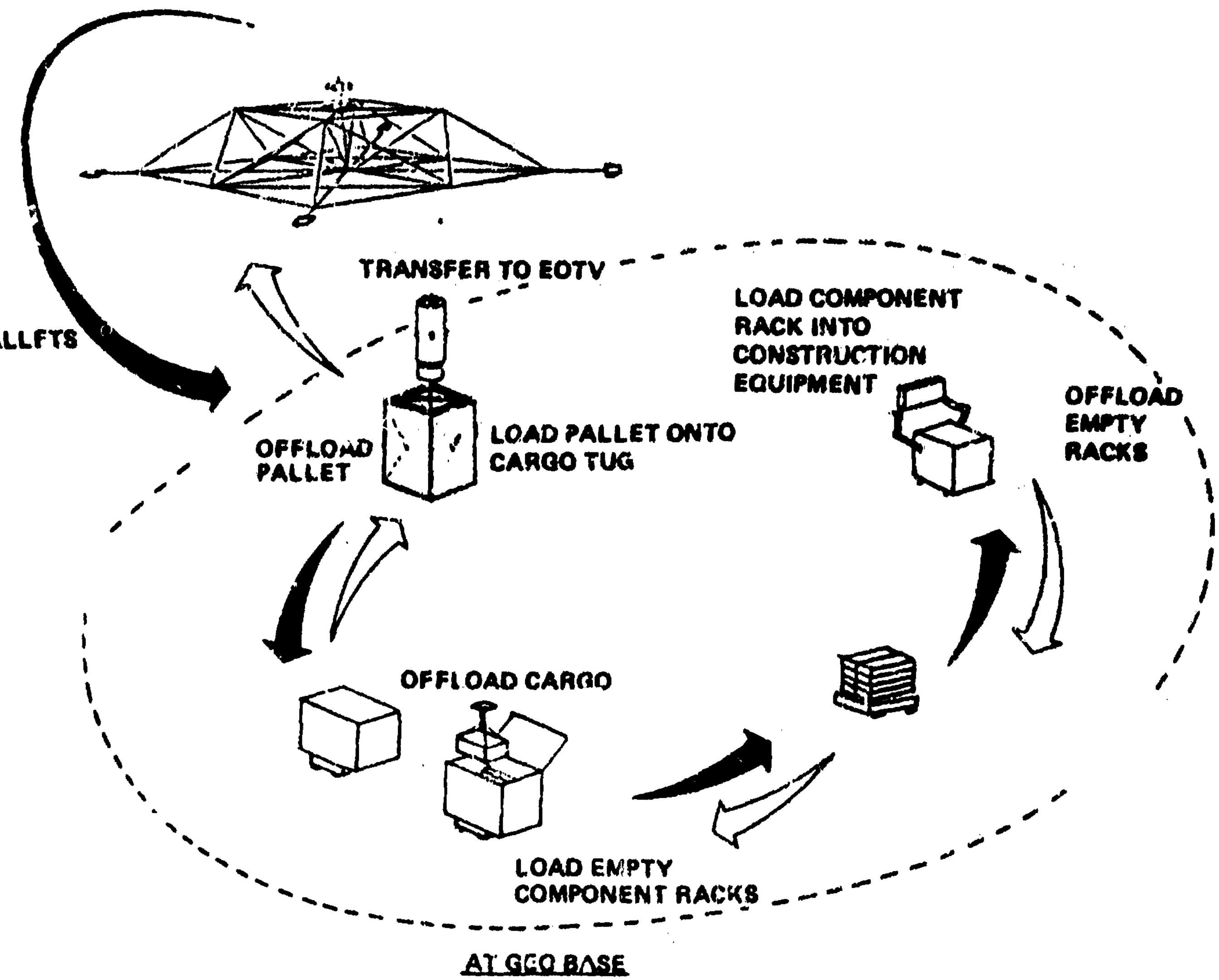
AT LEO BASE

CARGO HANDLING OPERATIONAL FLOW CYCLE (AT GEO BASE)

At the GEO, the cargo pallets are flown by cargo tugs from the EOTV to the GEO Base. These pallets are then transported to a cargo handling and storage area where the pallets are offloaded. The components are distributed to the subassembly factories, the construction equipment, the maintenance modules, or the mobile SPS maintenance equipment.

Some of the empty racks and magazines are repacked into the now-empty cargo pallets. The pallets are recycled back to Earth and the empty racks and magazines are recycled back to the factories.

Cargo Handling Operational Flow Cycle

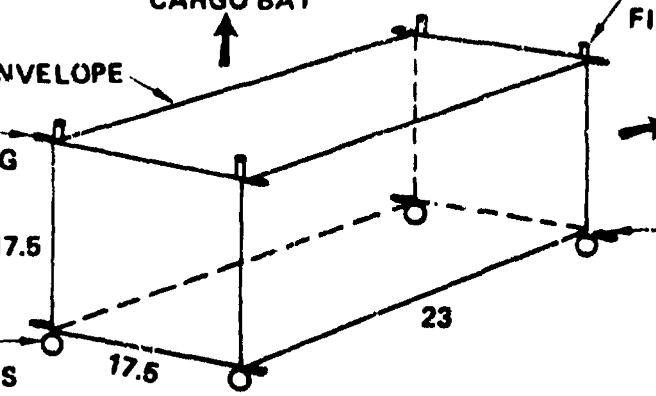


CARGO PALLET REQUIREMENTS

Tracing the flow of events through the entire cycle, the pallet and rack handling operations become visible. This figure illustrates some of the requirements imposed on the HLLV cargo pallet and the component racks by the handling operations.

Cargo Pallet Requirements

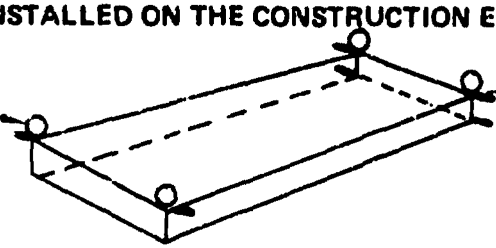
SPS-2876



- MUST BE CAPABLE OF INTERNALLY RECONFIGURING EACH PALLET TO ADAPT TO MULTIPLE COMBINATIONS OF PAYLOADS.

SOME COMPONENT RACK REQUIREMENTS

- RACK MUST CONTAIN A MINIMUM OF ONE DAY'S SUPPLY
- RACK LOADED AT THE FACTORY
- WHEREVER FEASIBLE, THE RACK SHOULD BE CONFIGURED TO BECOME THE COMPONENT MAGAZINE TO BE INSTALLED ON THE CONSTRUCTION EQUIPMENT (NO REPACKAGING DESIRED)



COMPONENT PACKAGING CONCEPTS

A large sampling of SPS and EOTV construction components were examined in detail in order to establish representative packaging concepts. This table is a sample of data derived for about 60 different components. This data is based upon the baseline operational scenario where it is required to construct one 5 gw SPS within 180 days, construct a fleet of EOTV's at the rate of one per 23 days, and to supply the propellants required by the EOTV's and POTV's during the 180 day period.

The configuration of each of the components or the material from which the components would be fabricated were derived from the descriptions given the Preferred Concept Description book (D180-25037-3). In most cases, the shipping unit (i.e., the number of components packaged together in a single package) was established either by (1) the total daily consumption of the component, or (2) by the magazine size that would be compatible with the construction equipment.

All of the "primary" components were detailed. These primary components are those that are either the most numerous, the most massive, and/or the largest. A careful look at the data shows that some of the most numerous components, e.g., batten end caps, do not require much payload volume and so they are classed as "secondary" components. Other secondary components are those that are small and/or few in number.

SPS Components Consumption Rate, Packing, and Shipping Data

SPS Components Consumption Rate, Packing, and Shipping Data

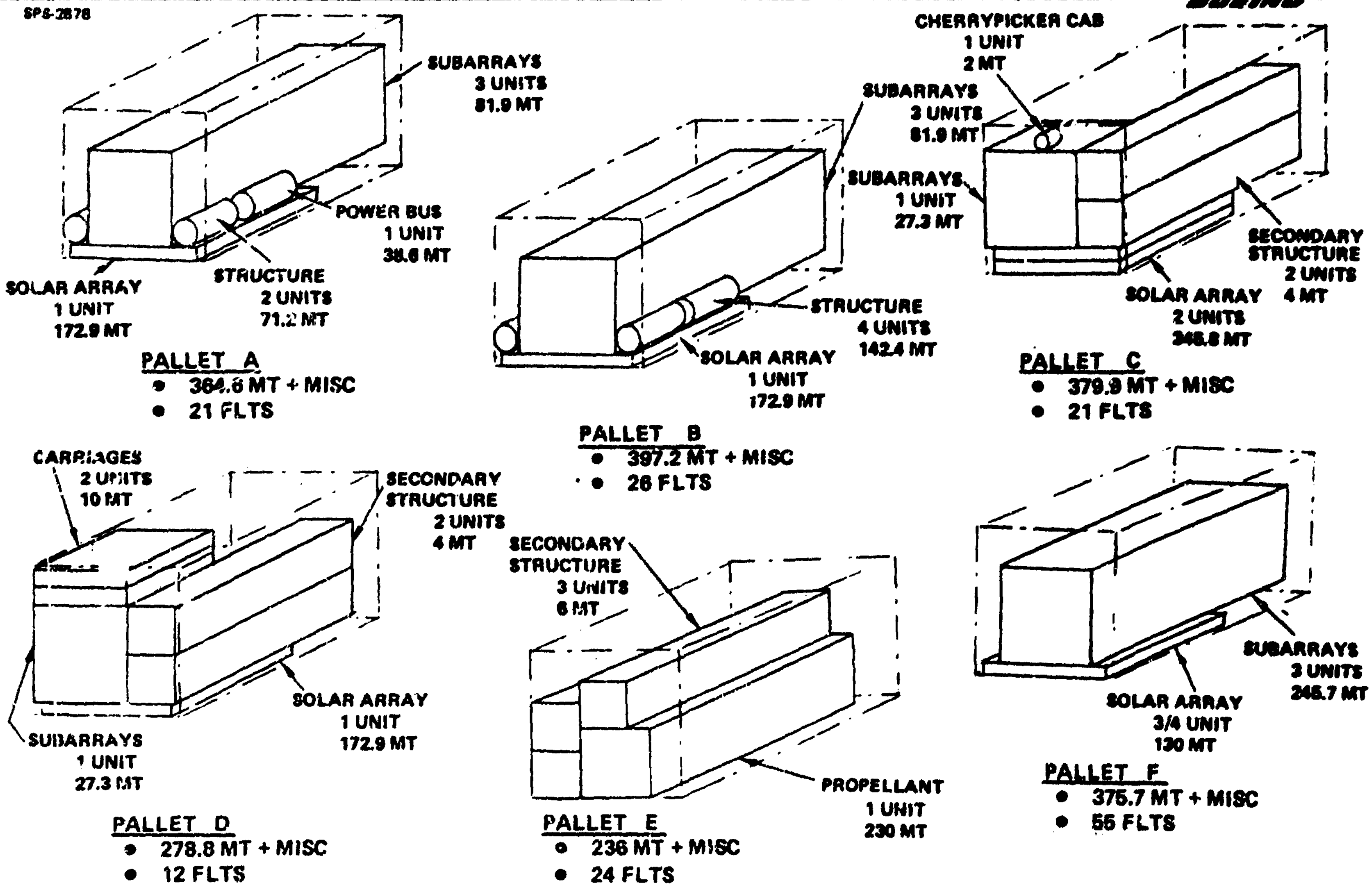
WBS	COMPONENT/ASSEMBLY	CONFIGURATION	QTY/5GW SPS	MASS/UNIT	CONSUMPTION RATE	SHIPPING UNIT	QTY OF SHIPPING UNITS/DAY
1.1.1.3	SOLAR BLANKET	772kg/m³ 0.048 m³ 1.23 14.9 33	5376	4675kg	37 blankets/day	1.5 15 13.21 37 units/[illegible]	1 @ 172975kg/[illegible]
1.1.1.4.1	MAIN POWER BUSES	3M0 2.75m wide 1mm thick	30	29084kg/reel	.28 reels/day	30 0.35 3 reels/[illegible]	1 @ 87000kg/[illegible] (1 time per week)
1.1.1.4.?	ACQUISITION POWER BUSES		8	3439kg/reel	.04 reels/day	8 reels/unit	1 @ 28000kg/[illegible] (1 time only)
1.1.1.4.3	SWITCH GEAR	2 1 1	100	408kg/unit	0.7 units/day	1 1 4 units	1 @ 1050kg/[illegible]
1.1.1.4.4	DISCONNECT SWITCHES	1 .2 .2	208	204kg/unit	1.4 units/[illegible]		
1.1.1.4.5	BLOCKING DIODES	.3 .056	9530	10kg/unit (est.)	66 units/day	.06 .3 .3 66 units	1 @ 780 kg/[illegible]
1.1.1.4.6	INTERCONNECT CABLING		304				
1.1.1.4.7	DC/DC CONVERTORS	3 1 2	7	100kg/unit		3 4 1 2 units	1 @ 200kg every other day
1.1.1.8.1	SOLAR ARRAY ANNEALER CARRIAGES	10 10 2	8	5000kg		8 10 10 3 units	1 @ 15000kg (16 times)
	ANNEALERS	10 10	178	45kg/unit	1.21 units/day	7 units	1 @ 560kg
	FLYING CHERRYPICKER CARRIAGE	10 10 2	4	5000kg			

SPS PAYLOAD PALLET SETS

The theoretical mass-limited payload delivery parameters are the following: (1) a total of 74319 MT are to be delivered to LEO within a six-month time period; (2) this will require 186 mass-limited flights; and (3) the launch rate would be 1.45 flights/day.

The packaging objective is to combine components into integrated payloads that come as close as possible to achieving 400 MT per pallet. This figure shows SPS payload sets that come within 10% of meeting this objective. A total of 202 flights per 6 months will be required to deliver these and a similar set of EOTV payloads.

SPS Payload Pallet Sets



CARGO PACKAGING ANALYSIS RECOMMENDATIONS

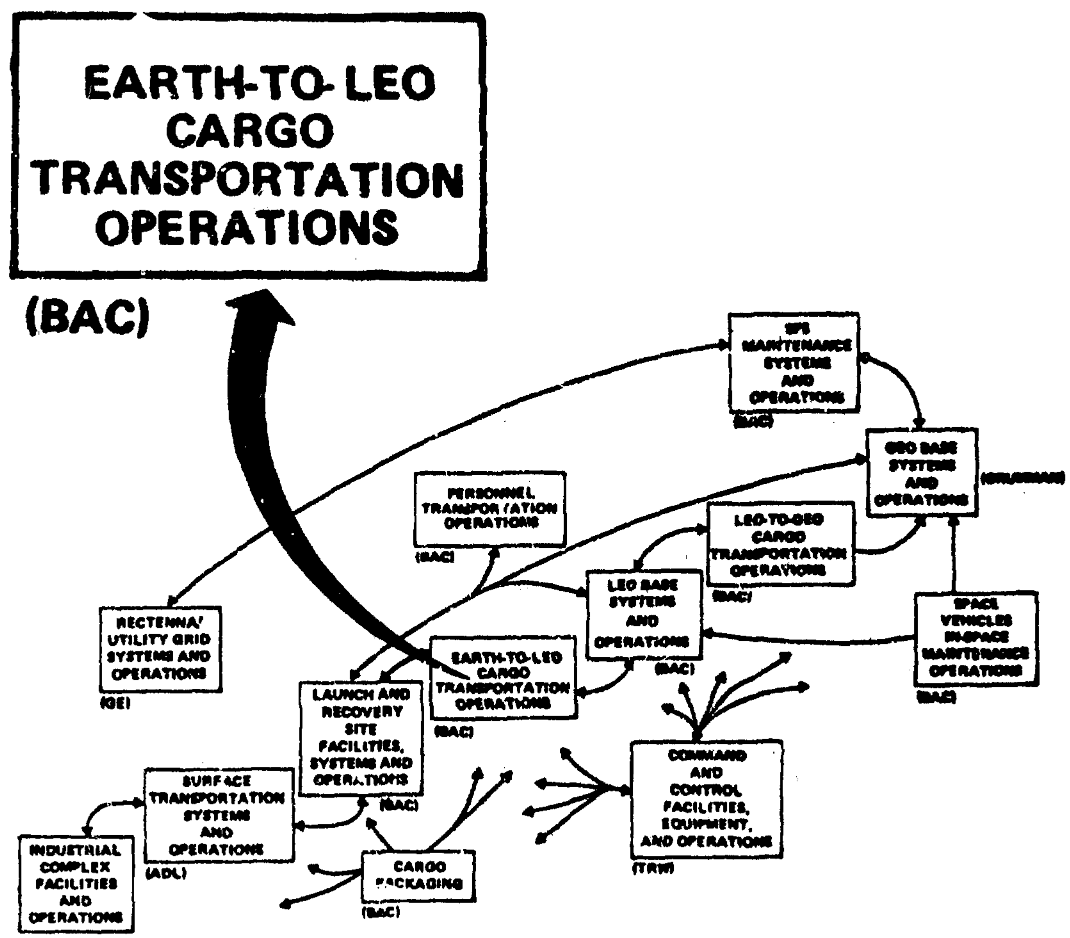
The recommendations that have resulted from this analysis are given in the table.

The cargo packaging analysis task will have to be updated periodically as the SPS program matures. It is recommended that in the next contractual study that a task be provided for creating a software package that can perform the packaging analysis This software would allow many alternatives to be explored that are beyond the capability of the manual analysis. As cargo transportation is the largest cost contributor to the SPS program and this transportation system is sized by the cargo packaging, it is imperative that this software be developed soon.

Task 45305 Cargo Packaging Analysis Recommendations

SPS-2892

- CONFIGURE THE HLLV TO ACCEPT A 17.5X17.5X21 M, 400 MT PAYLOAD PALLET.
- SHIP SOME COMPONENTS IN UNITS (RACKS) THAT CAN BE UTILIZED AS DISPENSING MAGAZINES ON CONSTRUCTION EQUIPMENT.
- COMBINE COMPONENTS INTO PAYLOAD SETS THAT CAN COME CLOSE TO ACHIEVING A 400 MT MASS-LIMIT.
- CONFIGURE THE PALLETS TO BE EASILY RE-CONFIGURED TO ACCEPT MULTIPLE COMBINATIONS OF PRIMARY AND SECONDARY PAYLOADS.
- ASSEMBLE CARRIAGES ON-ORBIT RATHER THAN DELIVERING THEM PREASSEMBLED.
- REASSESS ON-ORBIT ASSEMBLY OF SUBARRAYS AND ANTENNA SECONDARY STRUCTURE.
- USE 202 HLLV FLIGHTS PER 6 MONTHS AS THE MAXIMUM FLIGHT SCHEDULE TO SIZE THE HLLV FLEET SIZE AND LAUNCH/RECOVERY SITE.
- CREATE A CARGO PACKAGING ANALYSIS COMPUTER MODEL.


EARTH-TO-LEO CARGO TRANSPORTATION OPERATIONS
(BAC)
SPS MAINTENANCE SYSTEMS AND OPERATIONS
(BAC)
GEO BASE SYSTEMS AND OPERATIONS
PERSONNEL TRANSPORTATION OPERATIONS
(BAC)
LEO-TO-GEO CARGO TRANSPORTATION OPERATIONS
(BAC)
LEO BASE SYSTEMS AND OPERATIONS
(BAC)
SPACE VEHICLES IN-SPACE MAINTENANCE OPERATIONS
(BAC)
RECTENNA/ UTILITY GRID SYSTEMS AND OPERATIONS
(GE)
EARTH-TO-LEO CARGO TRANSPORTATION OPERATIONS
(BAC)
LAUNCH AND RECOVERY SITE FACILITIES, SYSTEMS AND OPERATIONS
(BAC)
SURFACE TRANSPORTATION SYSTEMS AND OPERATIONS
(ADL)
INDUSTRIAL COMPLEX FACILITIES AND OPERATIONS
(ADL)
CARGO PACKAGING
(BAC)
COMMAND AND CONTROL FACILITIES, EQUIPMENT, AND OPERATIONS
(TRW)

HLLV DOCKING SYSTEM ON THE LEO BASE

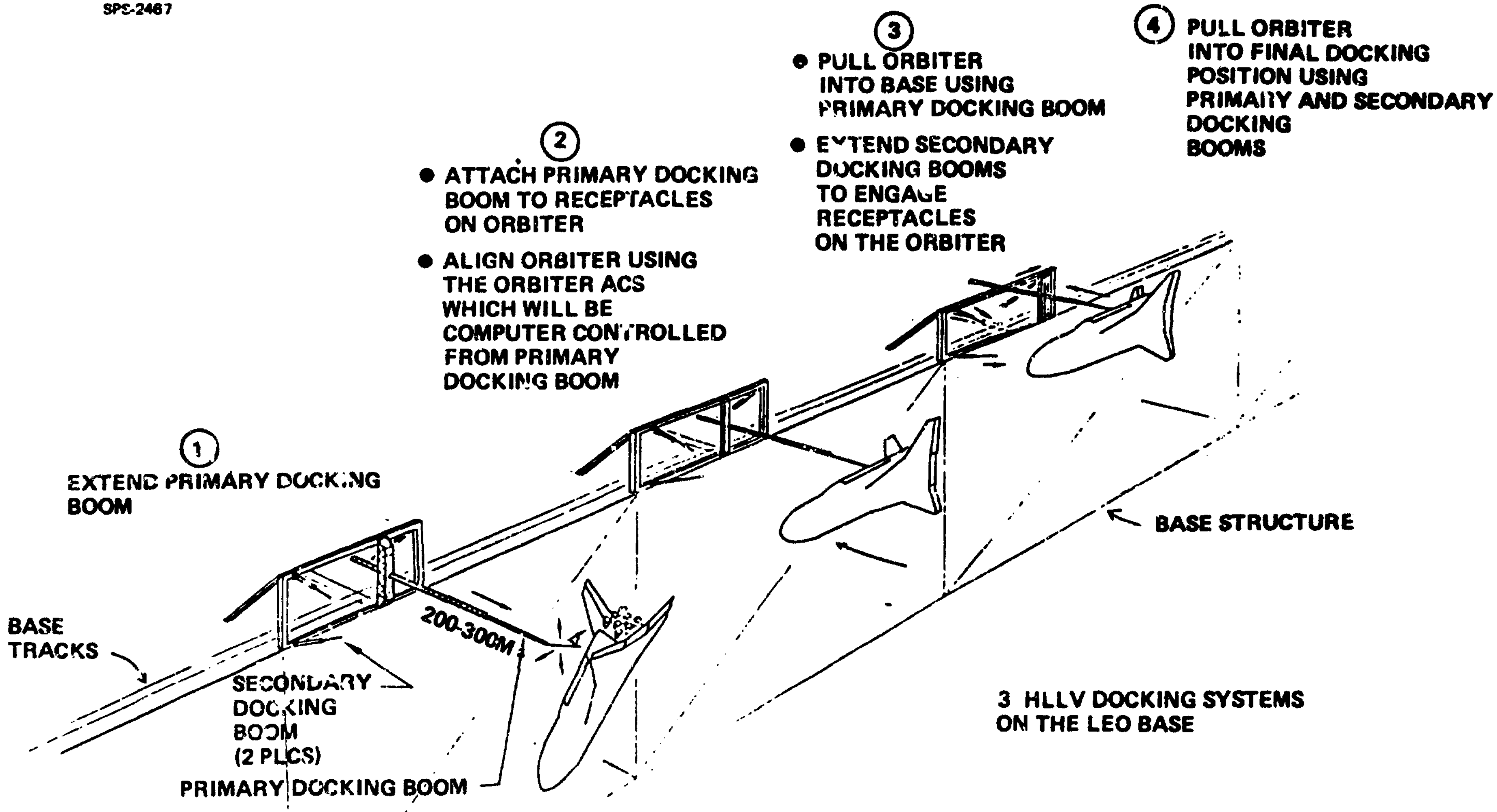
The cargo packaging analysis defined the requirement for an average of eight HLLV flights per week. The Launch and Recovery Site operations analysis shows a launch schedule of 2/1/2/1/2 HLLV launches per day each week. Therefore, it is necessary to provide docking facilities for two HLLV's at the LEO Base at one time. An additional docking facility is required as a spare bringing the total to three HLLV docking facilities.

The figure illustrates the HLLV Docking Facility concept. This facility is composed of a "window frame" structure on which is attached a primary docking boom and two secondary docking booms. The figure illustrates how these docking booms are employed to attach to the HLLV orbiter and to pull the vehicle into a docked position. These docking booms are operated from a control cab located at the lower center of each of the docking facilities.

It will be assumed that it will take one hour to perform the HLLV docking operations depicted.

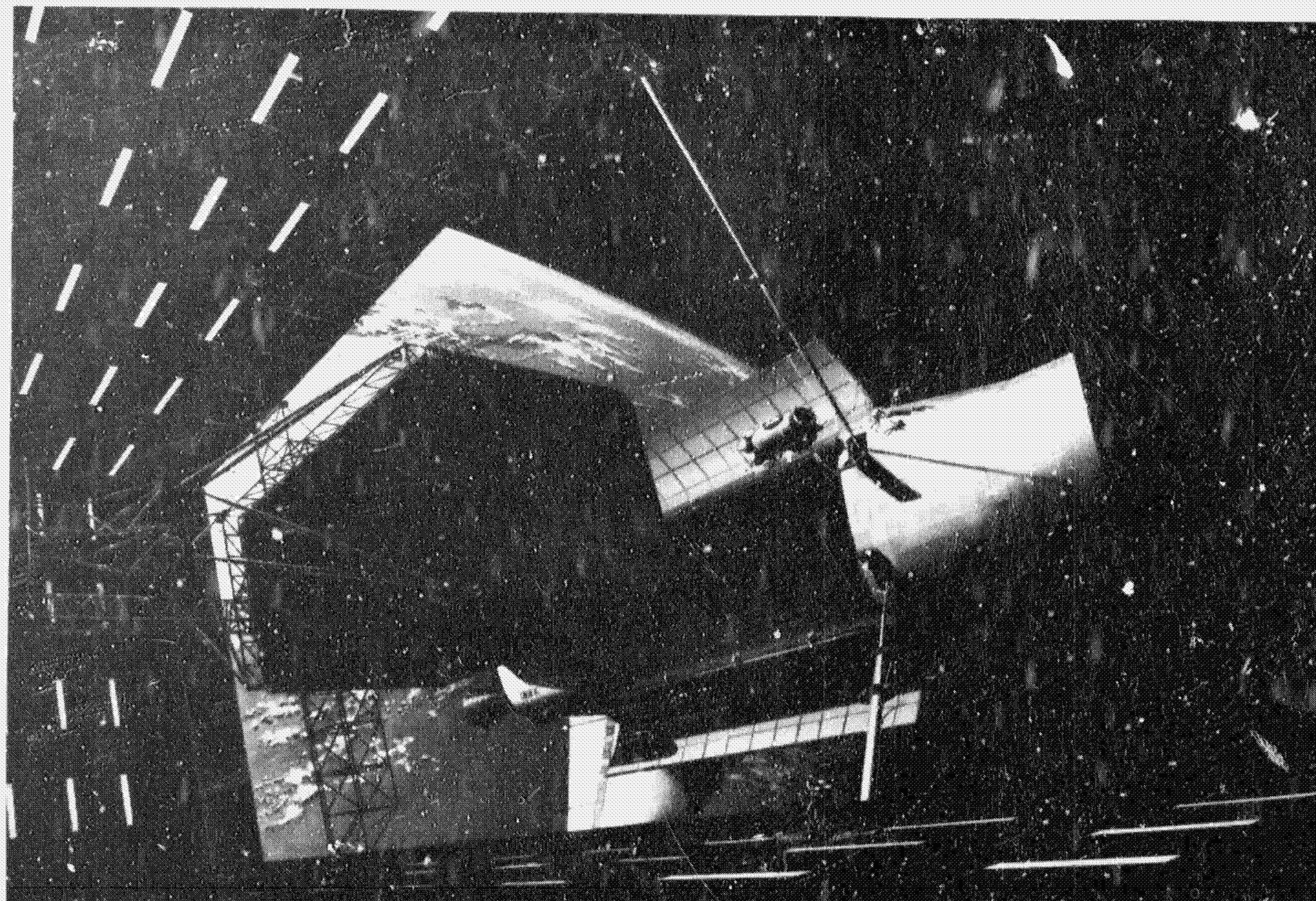
HLLV Docking Operations

SPS-2467



HLLV CARGO PALLET OFFLOADING

This illustration shows a close-up view of the HLLV cargo pallet offloading operation.

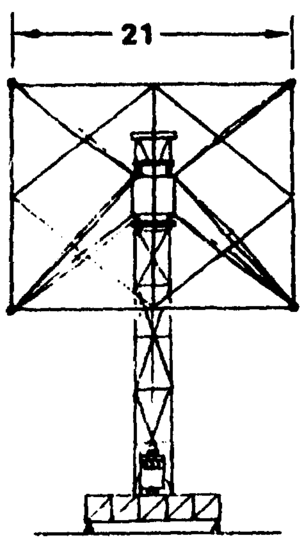


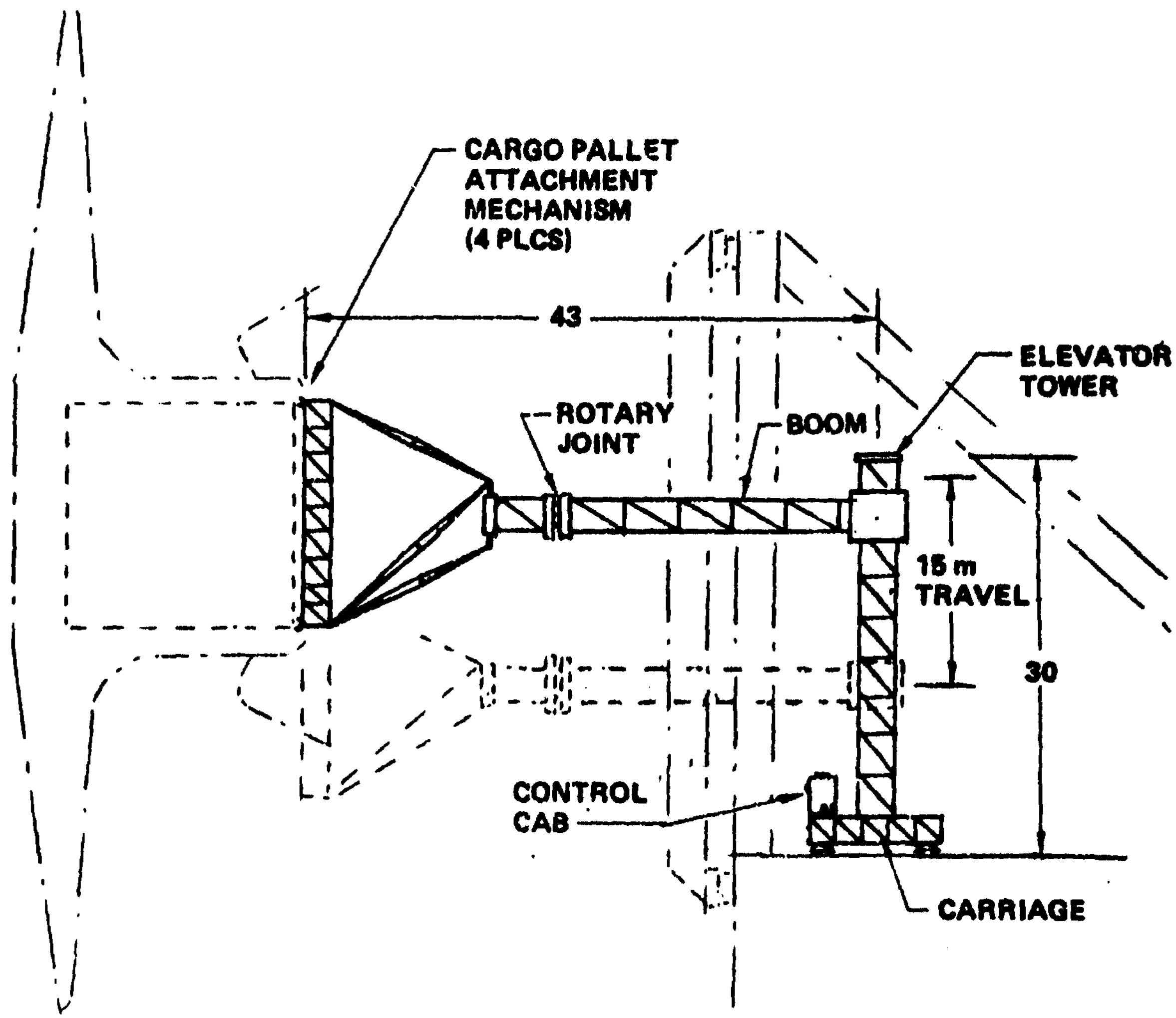
CARGO PALLET HANDLING MACHINE

A cargo pallet handling machine, such as shown in the figure, will be located at each of the two HLLV docking facilities. This machine reaches into the HLLV cargo bay and extracts the cargo pallet. The machine backs up, a cargo transporter is driven into a loading position, and the machine lowers the pallet onto the transporter. The transporter is driven to a cargo handling and storage area where the cargo will be processed.

Cargo Pallet Handling Machine (WBS 1.2.2.1.3.1)

SPS-2771





LEO BASE HLLV SUPPORT SYSTEMS AND CREW SIZE SUMMARY

This table summarizes the systems and crew required at the LEO Base to accommodate the HLLV docking and cargo offloading/loading operations.

LEO Base HLLV Support Systems and Crew Size Summary

HLLV SUPPORT SYSTEMS — 3 REQ'D [2]

HLLV DOCKING FACILITIES (WBS 1.2.2.1.6.1)

- o FRAME
- o PRIMARY DOCKING BOOM
- o SECONDARY DOCKING BOOMS (2 REQ'D)
- o CONTROL CAB (1 MAN)

o CARGO PALLET HANDLING MACHINE (WBS 1.2.2.1.3.1)	3 REQ'D [2]
o CARGO TRANSPORTERS (WBS 1.2.2.1.3.2)	3 REQ'D [2]
o CREW TRANSFER TUNNEL SYSTEM	3 REQ'D [2]

CREW SIZE [1]

o HLLV DOCKING FACILITY OPERATOR (2 FACILITIES) X (1 PER SHIFT) X (2 SHIFTS) =	4 OPERATORS
o CARGO PALLET MACHINE OPERATOR (2 MACHINES) X (1 PER SHIFT) X (2 SHIFTS) =	4 OPERATORS
o HLLV FACILITY SUPERVISOR (1 PER SHIFT) X (2 SHIFTS) =	2 SUPERVISORS
TOTAL	10 PEOPLE

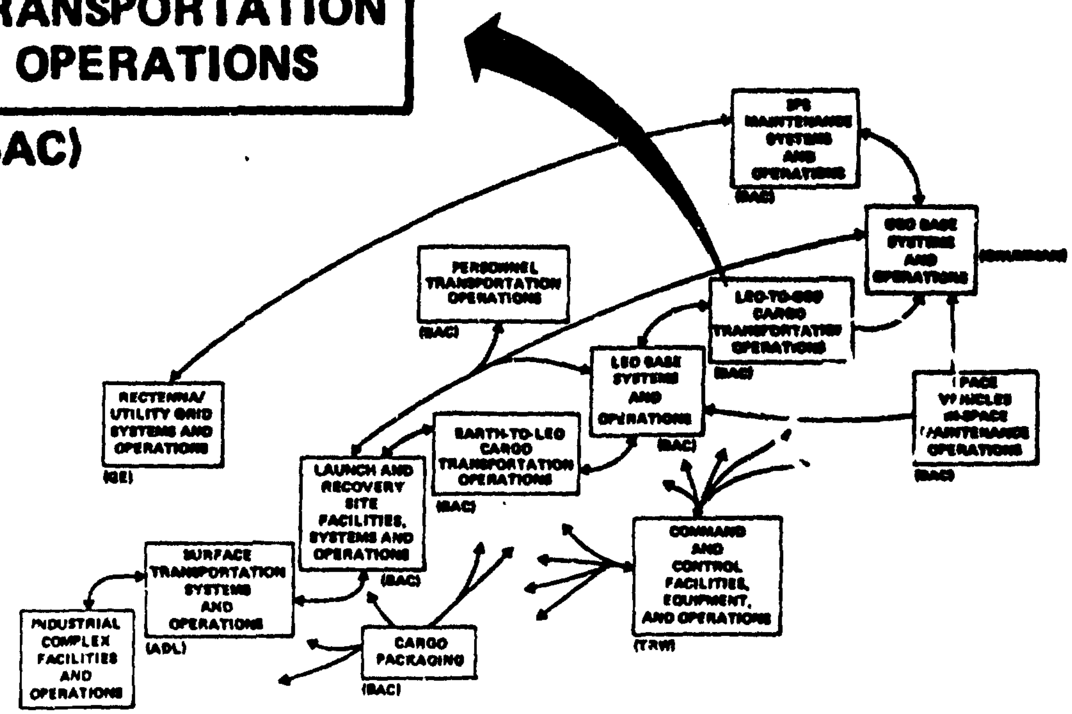
[1] DOES NOT INCLUDE COMMAND AND CONTROL PERSONNEL

[2] INCLUDES 1 SPARE

SPS-2908

LEO-TO-GEO CARGO TRANSPORTATION OPERATIONS

(BAC)



LEO-TO-GEO CARGO TRANSPORTATION SYSTEM OPERATIONS

This figure illustrates the overall LEO-to-GEO cargo transportation systems and operations.

At the LEO Base, an Electric Orbital Transfer Vehicle (EOTV) that has just returned from GEO is placed into a station keeping position approximately 1 km away from the base. A cargo tug flies over to the EOTV and picks up an empty cargo pallet and returns it to the LEO Base. (These empty pallets will eventually be returned to Earth on an HLLV.) A loaded cargo pallet is picked up at the base and transported to the EOTV by the cargo tug. This shuttling back and forth with empty and loaded cargo pallets continues until 10-20 cargo pallets are loaded onto the EOTV.

After the cargo pallets are loaded, the cargo tug picks up empty EOTV propellant pallets and returns them to the base. Two loaded propellant pallets will have been delivered to the LEO Base within HLLV cargo pallets. These two loaded propellant pallets are installed on the EOTV.

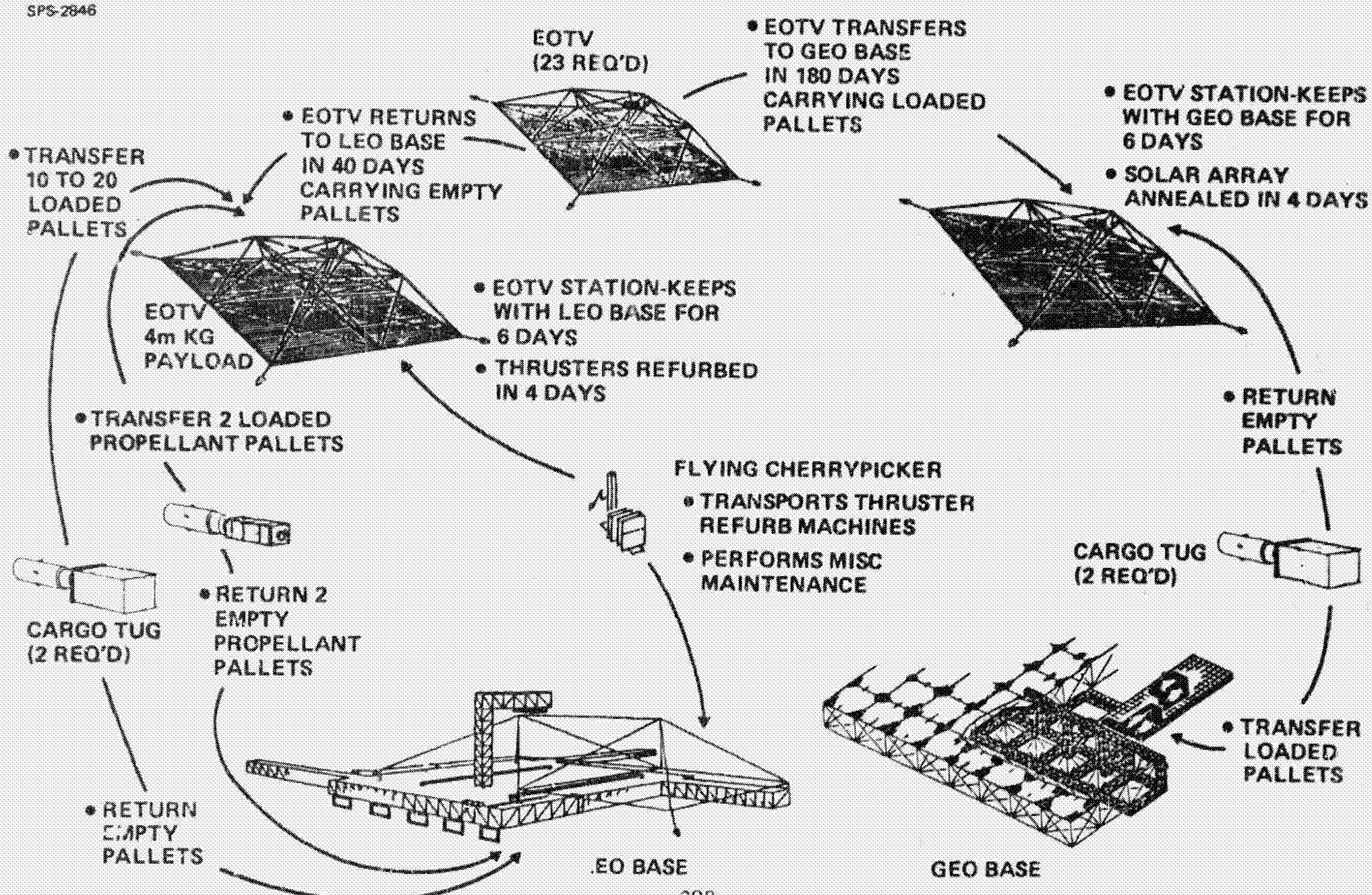
While the cargo and propellant resupply operations are underway, a flying cherrypicker transports four thruster refurbishment machines to the EOTV. These machines are installed onto the EOTV attitude control system electric thruster yokes. The machines are used to changeout the thruster accellerator grids. The flying cherrypicker is also used to attend to miscellaneous maintenance tasks while the thruster refurb machines automatically perform their operations. After four days, the thruster refurb machines are retrieved and returned to the LEO Base. The defective components are processed at the maintenance module to recondition them for reuse.

At the GEO Base, and EOTV that has just arrived from LEO is placed into a station keeping position approximately 1 km from the base. A cargo tug transfers the loaded cargo pallets to the base and empty cargo pallets to the EOTV in the same fashion as was done at the LEO Base. While the cargo pallet transfer operations are conducted, the annealing machines (that are permanently installed on the EOTV) are remotely activated. Over a four day period, the EOTV solar array is annealed.

LEO-to-GEO Cargo Transportation Systems and Operations

BOEING

SPS-2846

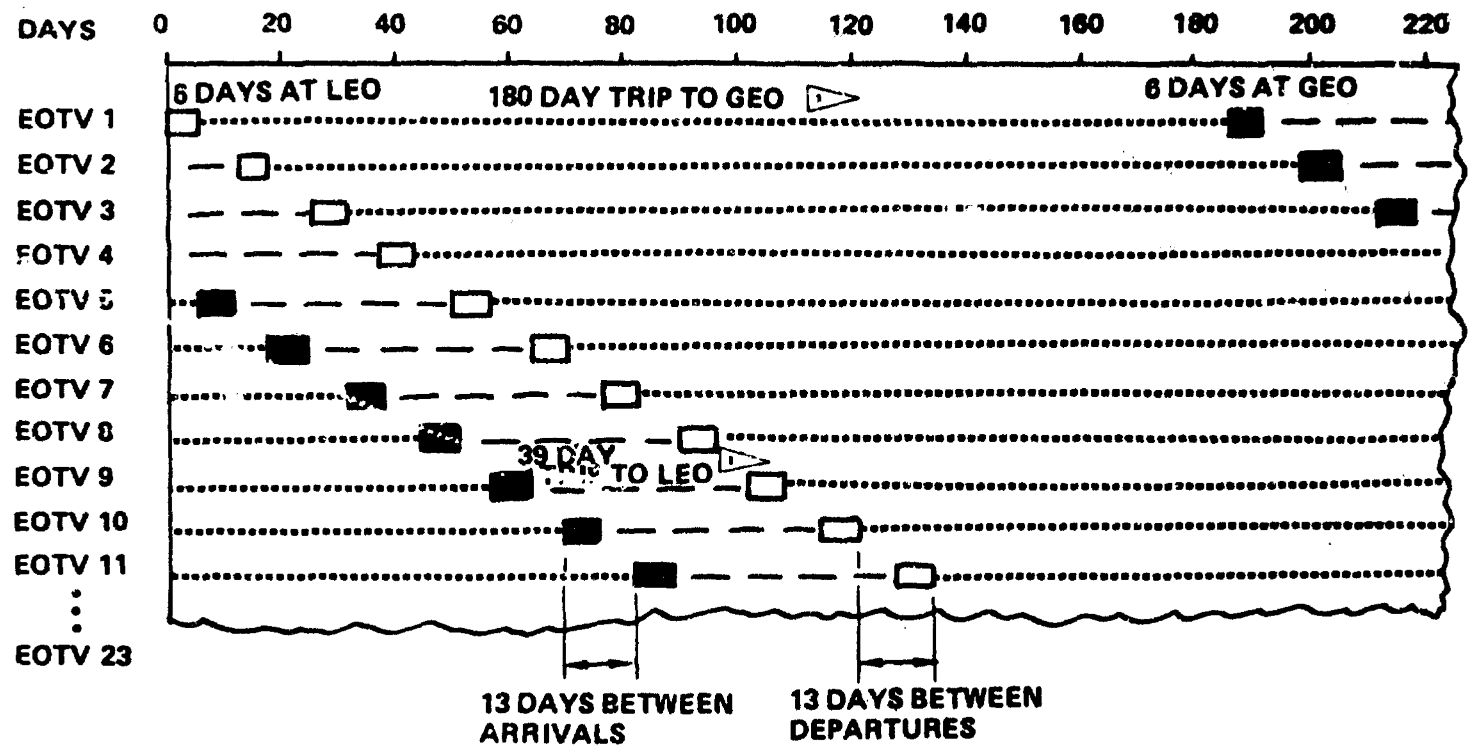


EOTV FLIGHT SCHEDULE

This figure shows the integrated EOTV flight schedule. A total of 28 EOTV flights are required during a one-year period in order to deliver the satellite components necessary to construct two 5gw satellites per year. This requires that an EOTV be launched to GEO every 13 days. A total of 22 vehicles are required to maintain an average of 28 deliveries per year when taking into account EOTV performance due to solar array degradation. One additional vehicle is added to the fleet as a spare giving a total of 23 vehicles.

EOTV Flight Schedule

SPS-2854



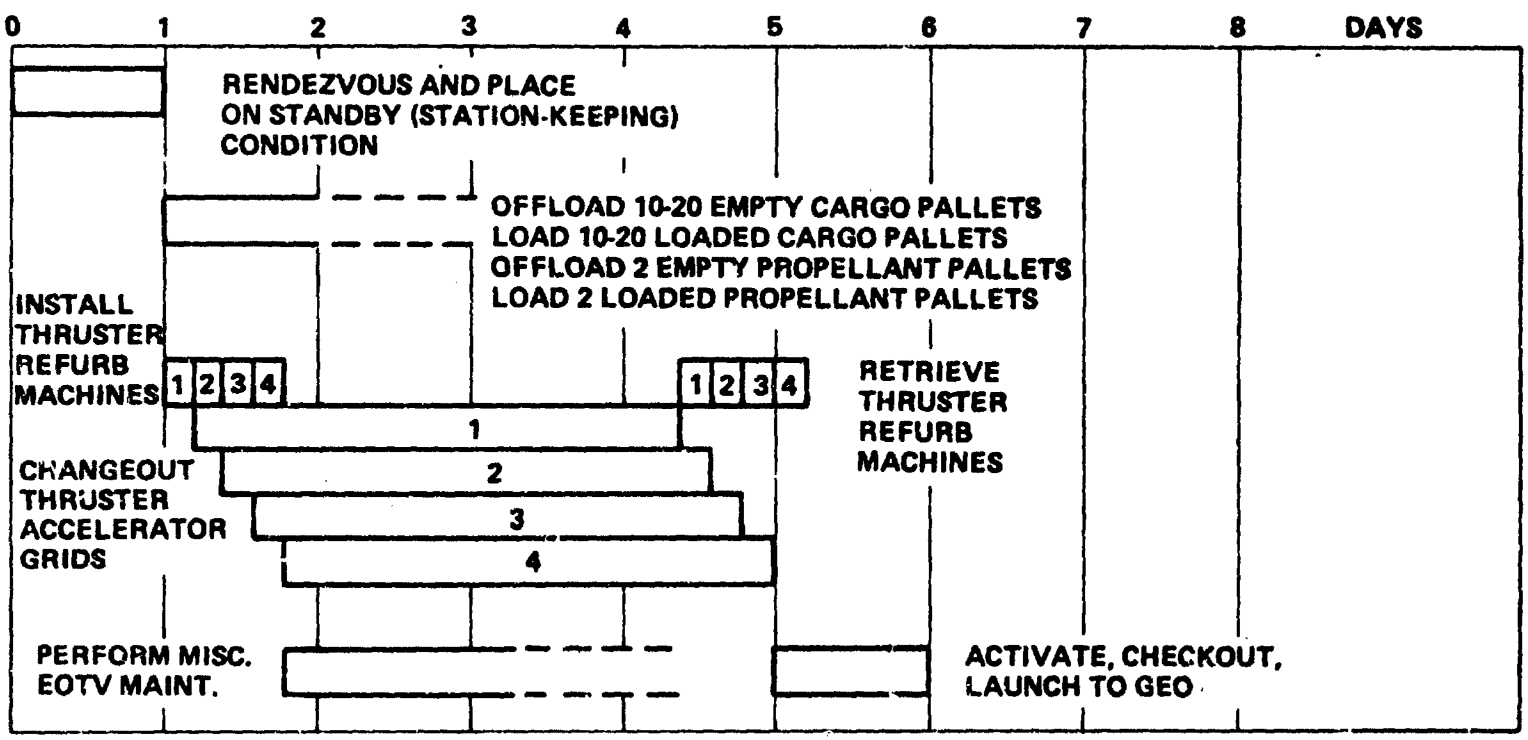
NOTE:
THIS FLIGHT SCHEDULE HAS NOT BEEN CALIBRATED TO TAKE INTO ACCOUNT A 6 DAY ON/1 DAY OFF WORKWEEK

THE 180 DAY AND 39 DAY TRIP TIMES ARE THE EOTV "FIRST TRIP" PERFORMANCE CHARACTERISTICS. SUBSEQUENT FLIGHTS WILL TAKE LONGER, DUE TO SOLAR ARRAY DEGRADATION

EOTV OPERATIONS AT LEO

This timeline shows the sequence of EOTV operations at the LEO Base during the six-day turnaround time. The thruster refurbishment operations are the pacing factor.

EOTV Operations at LEO



EOTV CARGO PLATFORM

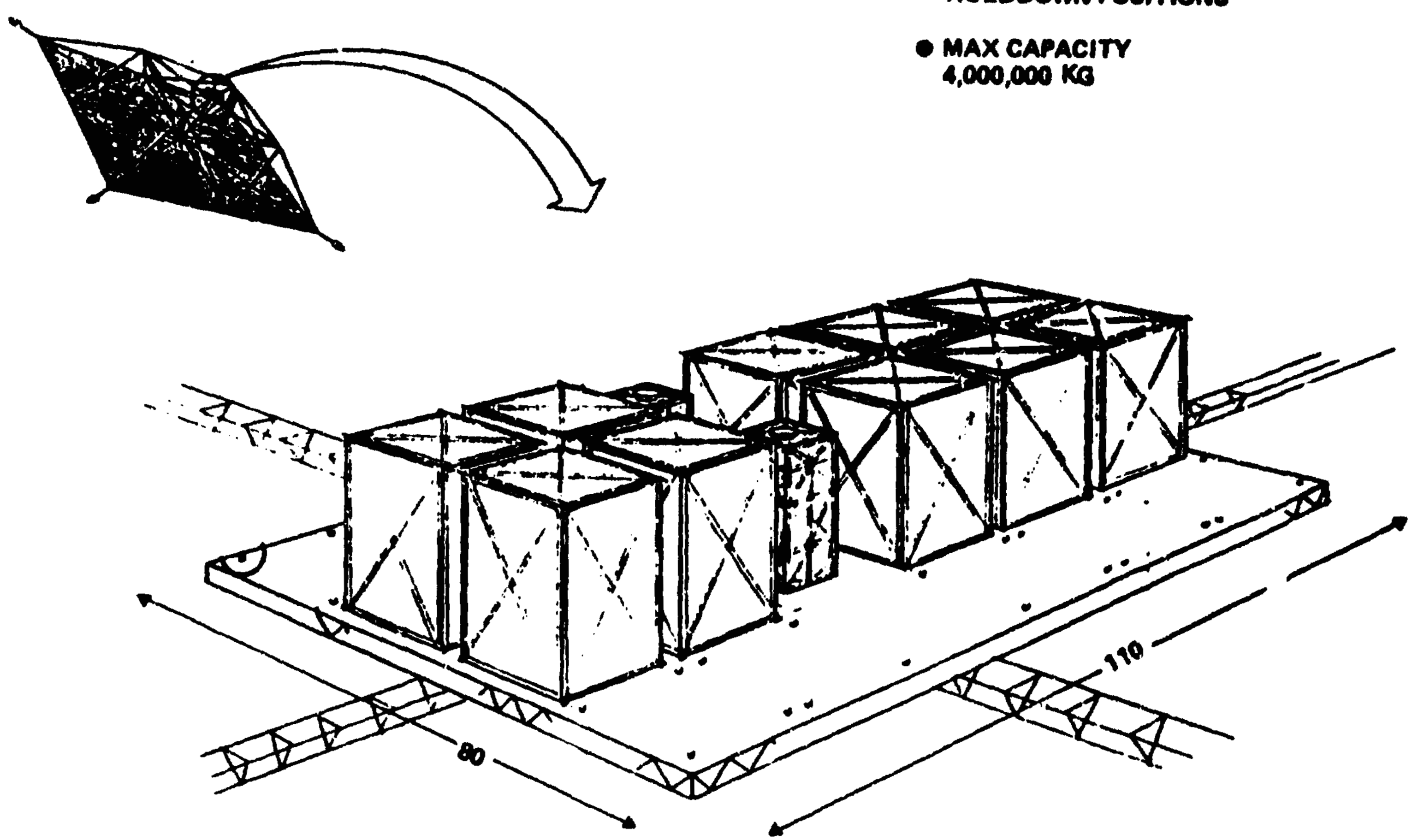
The reference EOTV is shown in this figure. Refer to WBS 1.3.2 for a detailed description of this vehicle.

The cargo platform that is located on the top of the EOTV is also shown. This platform has holddown provisions for up to 20 cargo pallets and two propellant pallets.

Twenty-three ETOV's are required (22 operational vehicles plus one spare).

EOTV Cargo Platform

- 20 CARGO PALLET HOLDDOWN POSITIONS
- MAX CAPACITY 4,000,000 KG



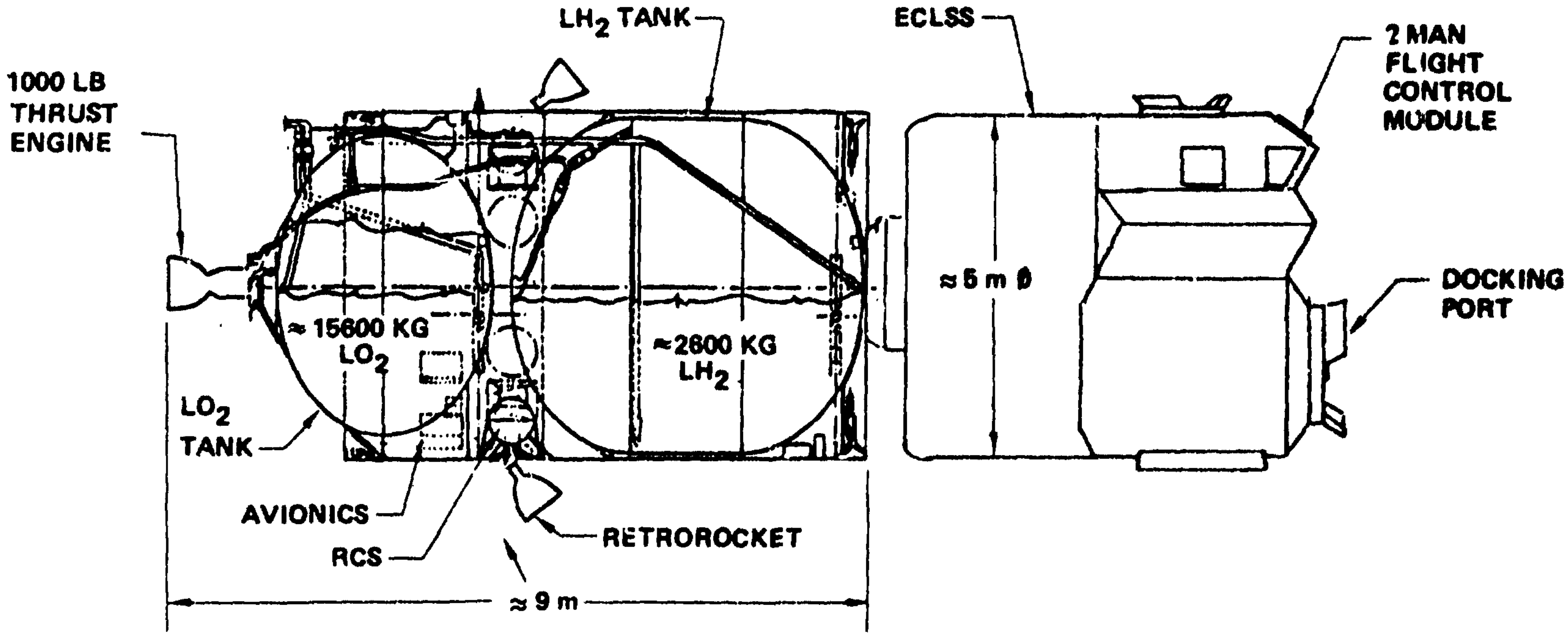
CARGO TUG FUNCTIONAL REQUIREMENTS

The conceptual configuration of the cargo tug is shown in this figure. The vehicle is used to (1) transport cargo pallets, and (2) to transport EOTV propellant pallets. The functional requirements for this vehicle are listed below. Two cargo tugs are required at each base (one operational plus one spare).

1. Two-man flight control cabin
2. Docking fixture on the nose of the crew cabin (mates with the pallet handling fixture, the propellant pallet, and to a docking port at the bases)
3. Electrical connector incorporated into the docking fixture that provides an interface with the crew cabin controls and displays used for these systems:
   a. Cargo pallet handling fixture gimbal
   b. Cargo pallet handling fixture attachment mechanisms
   c. Laser guidance system
   d. EOTV pallet holddown mechanisms
   e. Propellant tank fluid coupling mating mechanism
4. Must be able to back up TBD meters carrying a full load
5. Vehicle sizing criteria:
   a. 400,000 Kg payload (maximum)
   b. 1 Km trips
   c. Refuel after 12 round trips
   d. Transit time 5 to 30 minutes
6. Refueled from a propellant transfer system colocated with the docking port on the LEO and GEO bases
   a. Propellants delivered on a pallet carried within a cargo pallet

Cargo Tug

NOTE:
THIS IS A PRELIMINARY CONCEPT THAT HAS NOT BEEN OPTIMIZED



REFERENCE: BOEING AEROSPACE COMPANY OTV PROPOSAL, APRIL 1979

LEO BASE EOTV OPERATIONS SUPPORT SYSTEM AND CREW SIZE

This table summarizes the vehicles, systems, equipment, and crew required at the LEO Base to support the EOTV operations.

LEO Base EOTV Operations Support Systems and Crew Size

SPS-2891

<u>VEHICLES</u> (EXCLUDES MAINTENANCE VEHICLES - SEE TABLE 1)

2 CARGO TUGS (1 OPERATIONAL & 1 SPARE)

20 CARGO PALLET TRANSPORTERS

3 PROPELLANT PALLET TRANSPORTERS

<u>VEHICLE DOCKING PROVISIONS</u>

2 CARGO TUG DOCKING PORTS WITH PROPELLANT TRANSFER SYSTEM

2 FLYING CHERRYPICKER DOCKING PORTS

<u>SUPPORT EQUIPMENT</u>

- 2 CARGO PALLET HANDLING FIXTURES

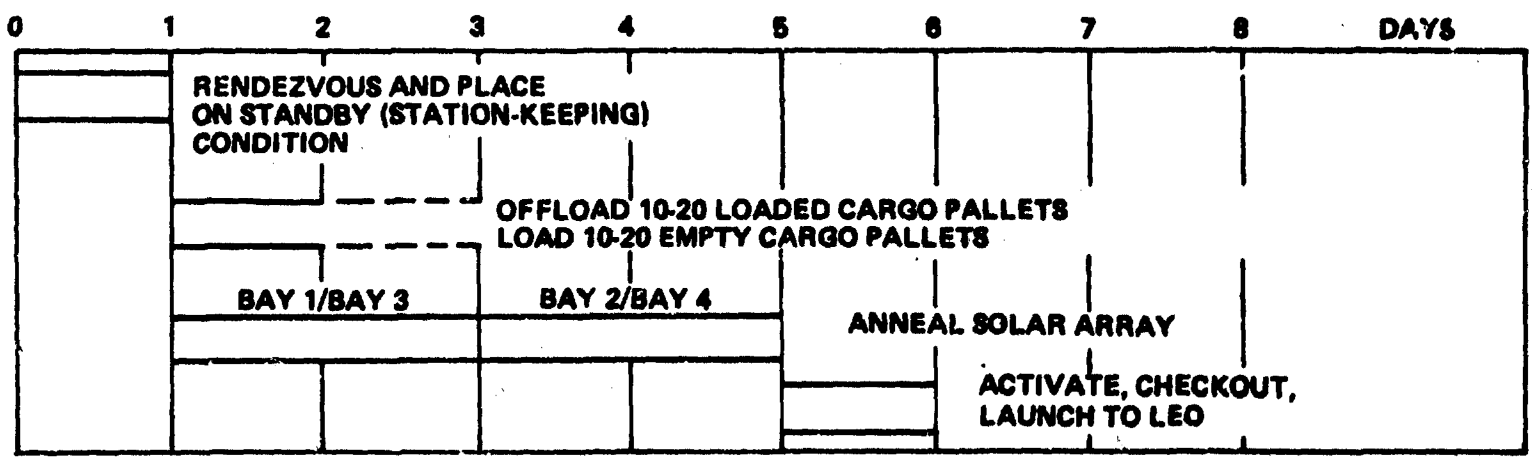
<u>LEO-TO-GEO CARGO TRANSPORTATION SUPPORT CREWS AT THE LEO BASE</u>

• CARGO TUG OPERATOR	2 PER SHIFT = 4	
• EOTV CONTROLLER	1 PER SHIFT = 2	
• TRAFFIC CONTROLLER	1 PER SHIFT = 2	(SHARED WITH THE HLLV, PLV, AND POTV FUNCTIONS)

EOTV OPERATIONS AT GEO

This figure shows the timeline for the EOTV operations conducted at the GEO Base. The table on the following page summarizes the support systems and crew.

EOTV Operations at GEO



GEO BASE EOTV OPERATIONS SUPPORT SYSTEMS AND CREW SIZE

This table summarizes the vehicles, equipment, systems, and crew required at the GEO Base to support the EOTV operations.

GEO Base EOTV Operations Support Systems and Crew Size

SPS-2890

VEHICLES

- 2 CARGO TUGS (1 OPERATIONAL & 1 SPARE)
- 20 CARGO PALLET TRANSPORTERS

VEHICLE DOCKING PROVISIONS

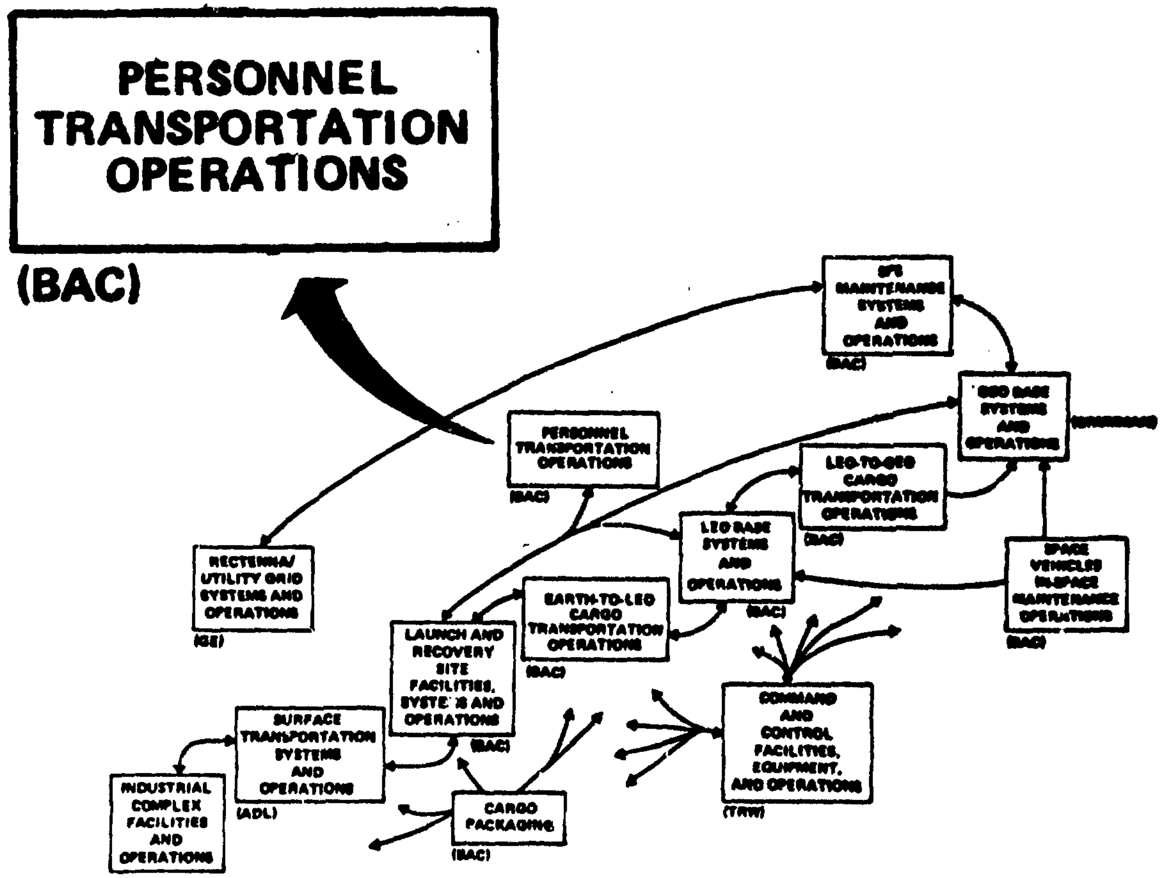
- 2 CARGO TUG DOCKING PORTS WITH PROPELLANT TRANSFER SYSTEM

SUPPORT EQUIPMENT

- 2 CARGO PALLET HANDLING FIXTURES

LEO-TO-GEO CARGO TRANSPORTATION SUPPORT CREW AT THE GEO BASE

• CARGO TUG OPERATOR	2 PER SHIFT = 4
• ANNEALING MACHINE OPERATOR	1 PER SHIFT = 2
• EOTV CONTROLLER	1 PER SHIFT = 2


PERSONNEL TRANSPORTATION OPERATIONS
(BAC)
PERSONNEL TRANSPORTATION OPERATIONS
RECTENNA/ UTILITY GRID SYSTEMS AND OPERATIONS
(GE)
LAUNCH AND RECOVERY SITE FACILITIES, SYSTE S AND OPERATIONS
EARTH-TO-LEO CARGO TRANSPORTATION OPERATIONS
LEO BASE SYSTEMS AND OPERATIONS
SURFACE TRANSPORTATION SYSTEMS AND OPERATIONS
(ADL)
INDUSTRIAL COMPLEX FACILITIES AND OPERATIONS
(ADL)
CARGO PACKAGING
COMMAND AND CONTROL FACILITIES, EQUIPMENT, AND OPERATIONS
(TRW)

PERSONNEL TRANSPORTATION SYSTEM
INTEGRATED PERSONNEL TRANSPORTATION SYSTEM OPERATIONS

The figure depicts the overall personnel transportation systems and operations.

At the Launch and Recovery Site, the orbital crew members are transported to the Personnel Launch Vehicle (PLV) launching pad. Seventy-five crew members are placed within a passenger module in the payload bay of the shuttle orbiter. This shuttle orbiter is mounted on a flyback booster and expendable external tank. The PLV is launched, the booster flies back to the launch site, and the shuttle and external tank continue toward LEO. The external tank is jettisoned and the orbiter boosts to LEO.

At the LEO Base, the orbiter is docked to the base and the passengers are offloaded into crew buses. Some of the passengers are moved to a transient crew quarters module where they are temporarily housed while awaiting their turn to be taken to the GEO Base. The crews destined for the LEO Base are taken to crew quarters modules.

The POTV is refueled from two POTV propellant pallets which were transferred to the LEO Base by the HLLV. The pallets were incorporated into the HLLV cargo pallets. These propellant pallets are removed from the cargo pallets and taken to the POTV operations area and installed on a docking and fuel transfer system.

The passenger module within the orbiter is reloaded with passengers returning to Earth.

The GEO crews are transported by crew buses to the OTV operations area where up to 160 passengers are loaded into a passenger module on a POTV. This POTV also includes a crew supply module and a flight control module. The latter is where the POTV flight crew operates the vehicle. The POTV is launched, the first stage returns to the LEO Base, and the second stage and attached modules continue on to GEO.

(Continued)

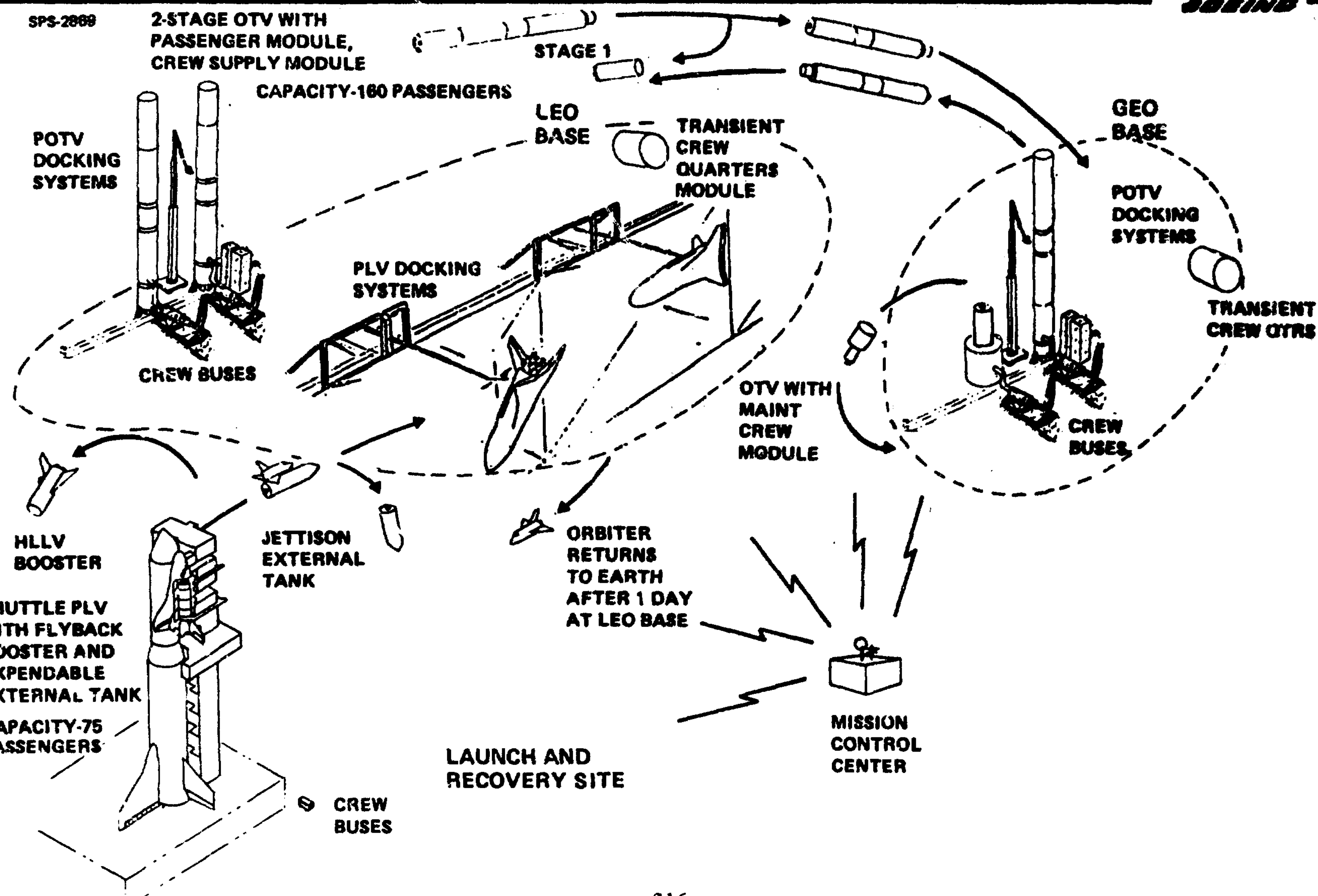
At the GEO Base, the POTV is docked and the passengers offloaded into crew buses. The crew buses transport the crew to their assigned crew quarters module.

Passengers awaiting return to LEO and then to Earth are temporarily housed in a GEO Base transient crew quarters. After the POTV has been reconfigured for the return trip, the passengers are loaded. The POTV then returns to the LEO Base.

Some of the crew transported to GEO will be members of a traveling SPS maintenance team. These people move into a crew quarters module attached to an OTV which will transport then from satellite to satellite. They will return to the GEO Base after 90 days.

All of the vehicles and personnel are managed by a cooperative network of groundbased Space Traffic Control, Transport Vehicle, Launch and Recovery, LEO Base, and GEO Base command and control centers.

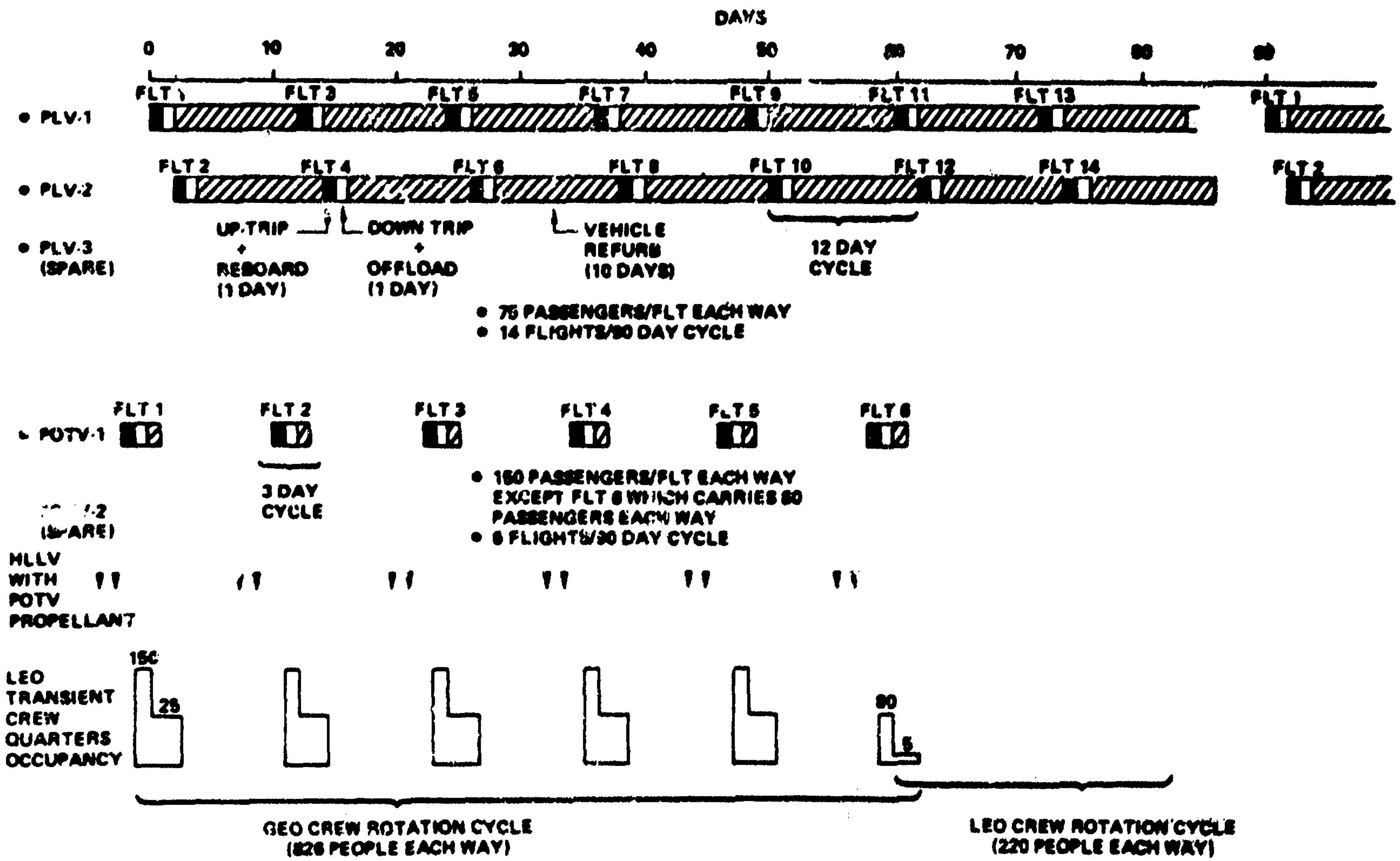
Personnel Transportation System



PERSONNEL TRANSPORTATION SYSTEM SCHEDULE

The figure shows the integrated personnel transportation schedule. This schedule requires that there be three PLV's (two operational plus one spare) and two POTV's (one operational and one spare). These vehicles move 826 crew members each way over a 60-day period of time. It takes six POTV flights and 11 PLV flights to accomplish this GEO crew rotation. The 220 LEO-based crew members are rotated over a 30-day period and requires four PLV flights.

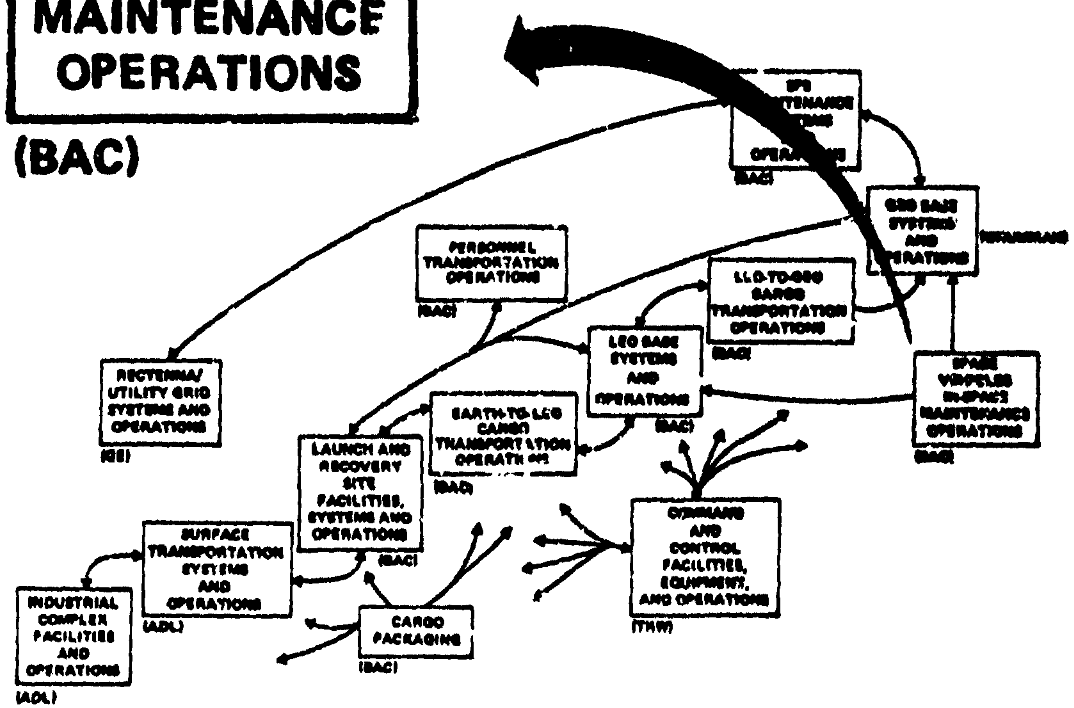
Personnel Transportation System Schedule



SPS-2903

SPACE VEHICLES IN-SPACE MAINTENANCE OPERATIONS

(BAC)

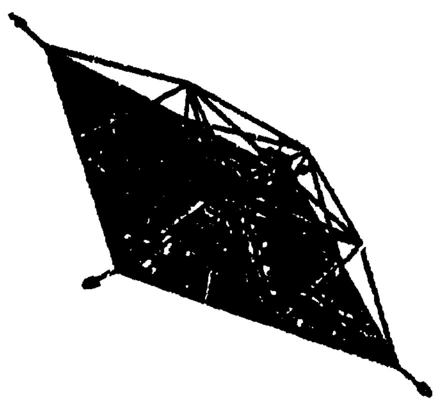
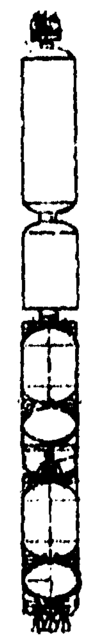
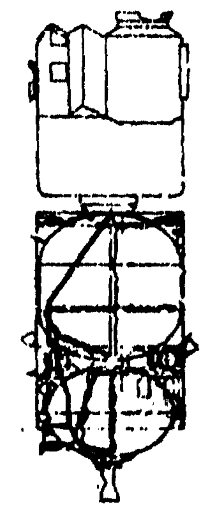
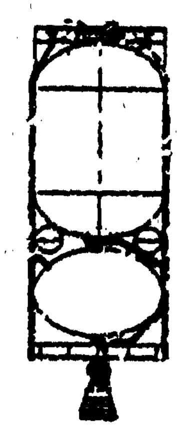


SPACE VEHICLES AND IN-SPACE MAINTENANCE LOCATIONS

This figure summarizes the space vehicles that will require in-space maintenance, the number of vehicles in the fleet, where the vehicles are maintained, and the frequency of maintenance.

Space Vehicles and In-Space Maintenance Locations

SPS-2786

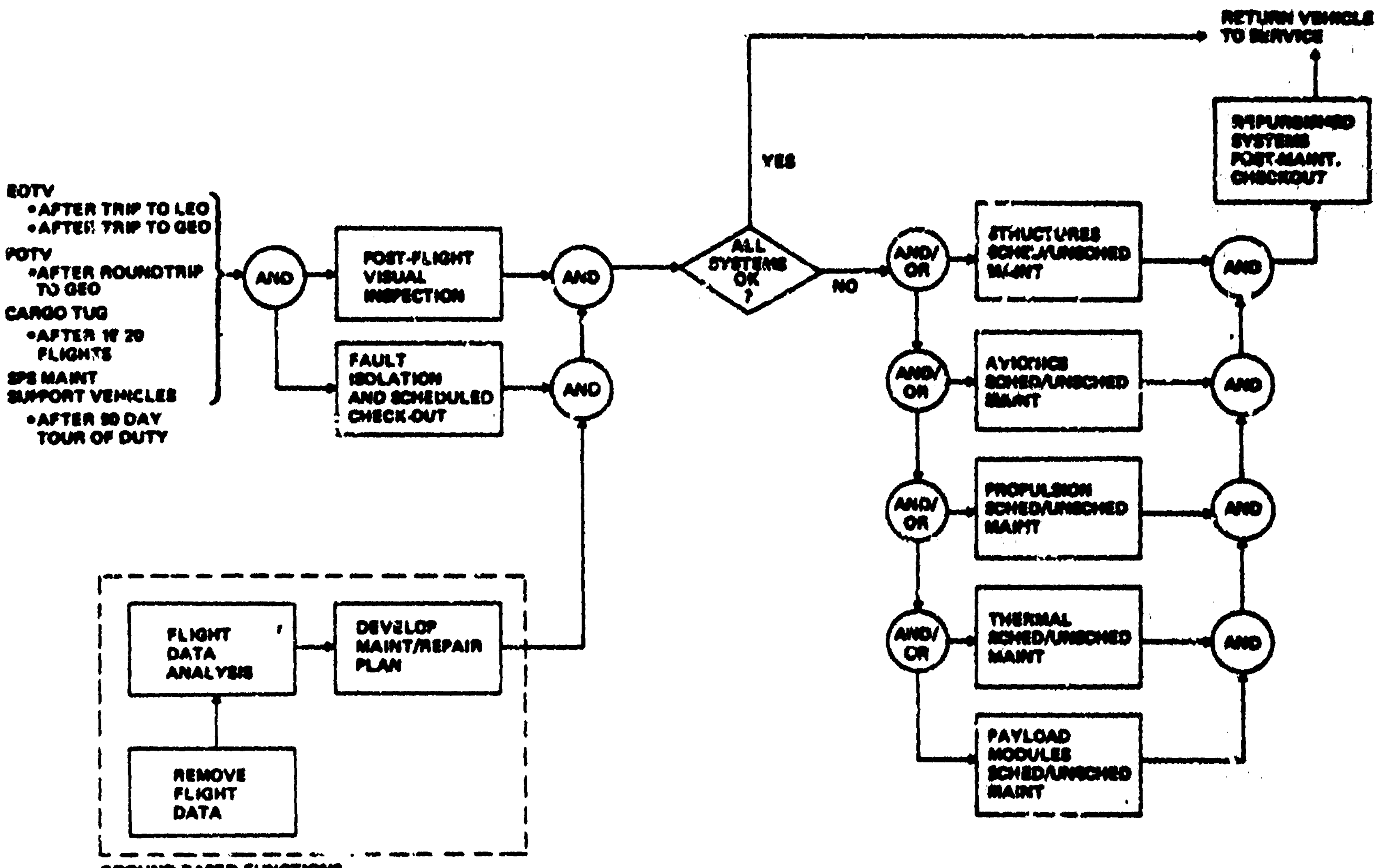
	EOTV	POTV	CARGO TUG	SPS MAINT SUPPORT VEHICLES
VEHICLE [1]				
NO. OF VEHICLES IN FLEET	• 23	• 2 (1 + 1 SPARE)	• 2 AT LEO BASE • 2 AT GEO BASE	• 5 (4 + 1 SPARE)
WHERE MAINTAINED	• SOLAR ARRAY ANNEALED AT GEO BASE • EVERYTHING ELSE MAINTAINED AT LEO BASE	• LEO BASE	• LEO BASE • GEO BASE	• GEO BASE
MAINT FREQUENCY	• AT LEO BASE EVERY TRIP • AT GEO BASE EVERY TRIP	• AFTER EVERY ROUNDTRIP	• AFTER 15-20 FLTS	• AFTER 90 DAYS TOUR OF DUTY

[1] THE HLLV AND PLV ORBITERS ARE MAINTAINED ON EARTH - NO IN-SPACE MAINTENANCE IS PLANNED

SPACE VEHICLE IN-SPACE MAINTENANCE CREW

This table lists the vehicle maintenance crews stationed at each of the bases. If the maintenance jobs require more manpower, maintenance technicians and mechanics can be borrowed from other maintenance crews at the base (e.g., from the base system maintenance crew). If the problem is very complex, specialists will be sent to the base from Earth. With the exception of the EOTV, the vehicle stages could be slipped back to Earth for major refurbishment if it becomes unfeasible to repair it in space.

Space Vehicles In-Space Maintenance Functional Flow



SPS MAINTENANCE ANALYSIS

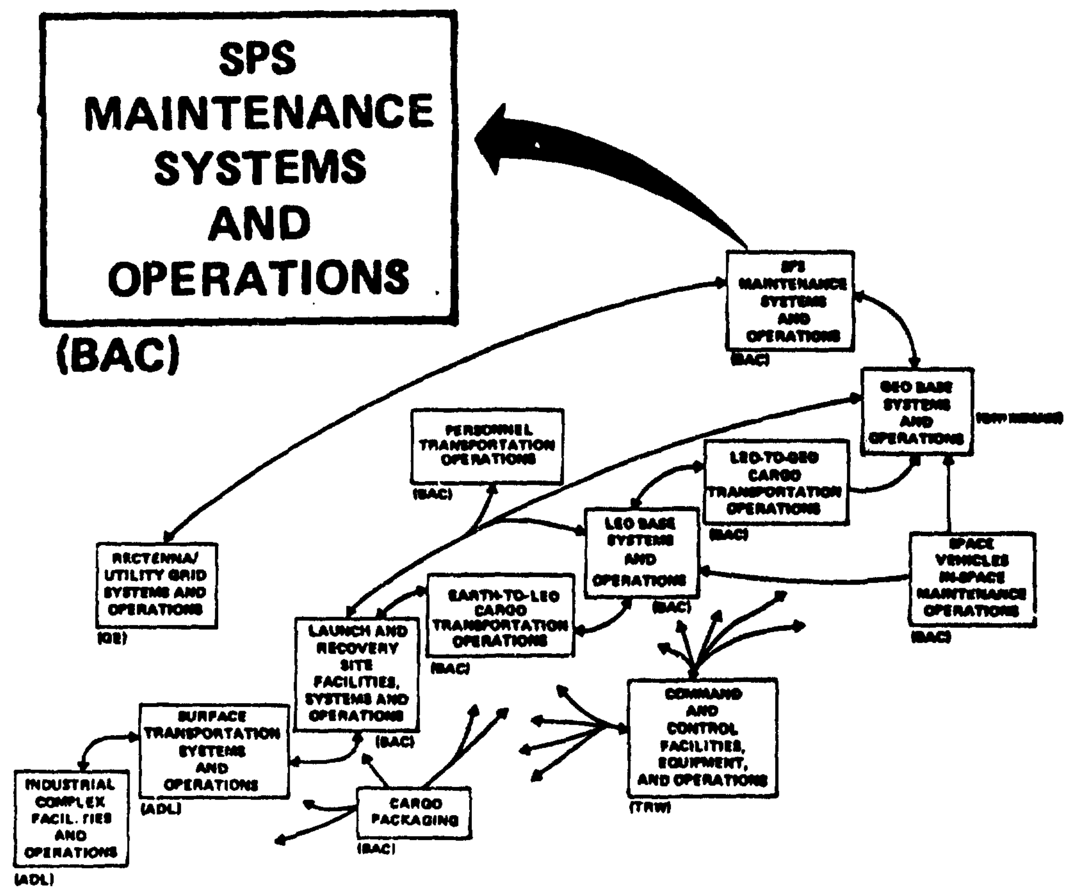
There were four main subtasks to this satellite maintenance analysis task: (1) definition of the maintenance access systems that would be used for getting maintenance equipment to all locations on the satellite where maintenance will be performed; (2) definition of the maintenance plans for some selected components; (3) definition of the maintenance support facilities, equipment, crew, and operations that would be located at the GEO base; and (4) creation of an integrated maintenance operations plan.

Space Vehicle In-Space Maintenance Crew

JOB TITLE	NUMBER REQ'D [1] LEO BASE	NUMBER REQ'D [1] GEO BASE
VEHICLE MAINTENANCE SUPERVISOR [4]	1	1
VEHICLE MAINTENANCE ENGINEER [4]	1	1
VEHICLE MAINTENANCE TECHNICIANS [4]		
• PROPULSION AND CRYOGENICS	1	1
• ELECTRICAL/ELECTRONIC SYSTEMS	1	1
• MECHANICAL/STRUCTURAL SYSTEMS	1	1
• ENVIRONMENTAL CONTROL LIFE SUPPORT SYSTEMS	1	1
VEHICLE MAINTENANCE MECHANICS [4]		
• ELECTRICAL SYSTEMS	2	1
• MECHANICAL/STRUCTURAL SYSTEMS	2	1
• VACUUM/GAS/FLUID/CRYO SYSTEM	2	1
INSPECTORS [4]		
• SAFETY	1	1
• QUALITY CONTROL	1	1
CHERRYPICKER OPERATOR	5 [2]	5 [2]
THRUSTER REFURBISHMENT MACHINE OPERATOR	2	-
COMPONENT REFURBISHMENT MECHANICS AND TECHNICIANS	[3]	[3]
ANNEALING MACHINE OPERATOR	-	2
OTHER	1	1
TOTAL	22	19

[1] Number listed is the number of people required to staff the position over 2 shifts
[2] Includes flying cherrypicker operators
[3] Technicians and mechanics perform the refurbishment tasks between the times when they work at the vehicles
[4] These crew members will be EVA qualified

SPS-2909


SPS
MAINTENANCE
SYSTEMS
AND
OPERATIONS
(BAC)
SPS MAINTENANCE SYSTEMS AND OPERATIONS
(BAC)
GEO BASE SYSTEMS AND OPERATIONS
PERSONNEL TRANSPORTATION OPERATIONS
(BAC)
LEO-TO-GEO CARGO TRANSPORTATION OPERATIONS
(BAC)
LEO BASE SYSTEMS AND OPERATIONS
(BAC)
SPACE VEHICLES IN-SPACE MAINTENANCE OPERATIONS
(BAC)
RECTENNA/ UTILITY GRID SYSTEMS AND OPERATIONS
(GE)
EARTH-TO-LEO CARGO TRANSPORTATION OPERATIONS
(BAC)
LAUNCH AND RECOVERY SITE FACILITIES, SYSTEMS AND OPERATIONS
(BAC)
COMMAND AND CONTROL FACILITIES, EQUIPMENT, AND OPERATIONS
(TRW)
SURFACE TRANSPORTATION SYSTEMS AND OPERATIONS
(ADL)
INDUSTRIAL COMPLEX FACIL. TIES AND OPERATIONS
(ADL)
CARGO PACKAGING
(BAC)

INTEGRATED MAINTENANCE MISSION CONCEPTS

Launch and Recovery Site Maintenance Support Operations

There are 260 maintenance crewmembers that must be rotated every 90 days. These crewmembers will be delivered to LEO via personnel launch vehicles (PLV's), along with the other SPS spaceworkers.

The replacement components will be delivered to the Launch and Recovery Site where these goods will be integrated into the HLLV payloads along with construction components. These components will be relatively small (motors, bearings, switches, pumps, electrical parts, etc.). It should, therefore, be possible to include pallets of these components in construction component payloads. Dedicated HLLV flights for transporting replacement components is not warranted.

LEO Base Maintenance Support Operations

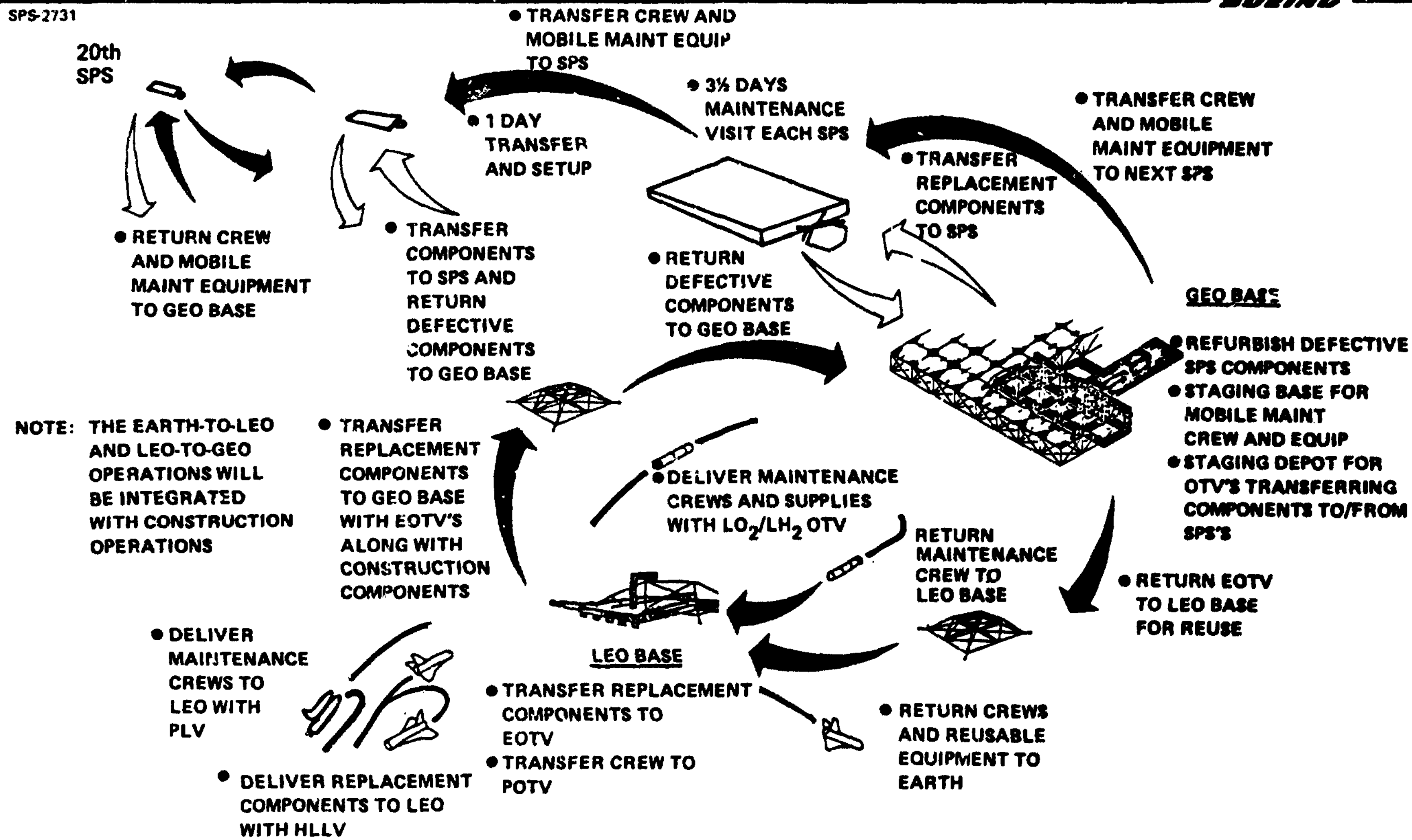
The maintenance crew will be transferred from the PLV's onto Personnel Orbit Transfer Vehicles (POTV's). The crew is transferred to GEO on the POTV in a matter of hours.

The pallets of replacement parts will remain integrated with the construction component HLLV payload pallets. These pallets will be transferred from the HLLV directly onto the electric orbit transfer vehicle (EOTV). After 10 HLLV's have been offloaded onto the EOTV, this vehicle starts a 180 day trip to GEO.

Geo Base Maintenance Support Operations

There are three major maintenance support operational areas at the GEO base: 1) OTV operations area, 2) pallet loading/offloading and storage operations area, and 3) refurbishment operations area.

Integrated Maintenance Mission Concept



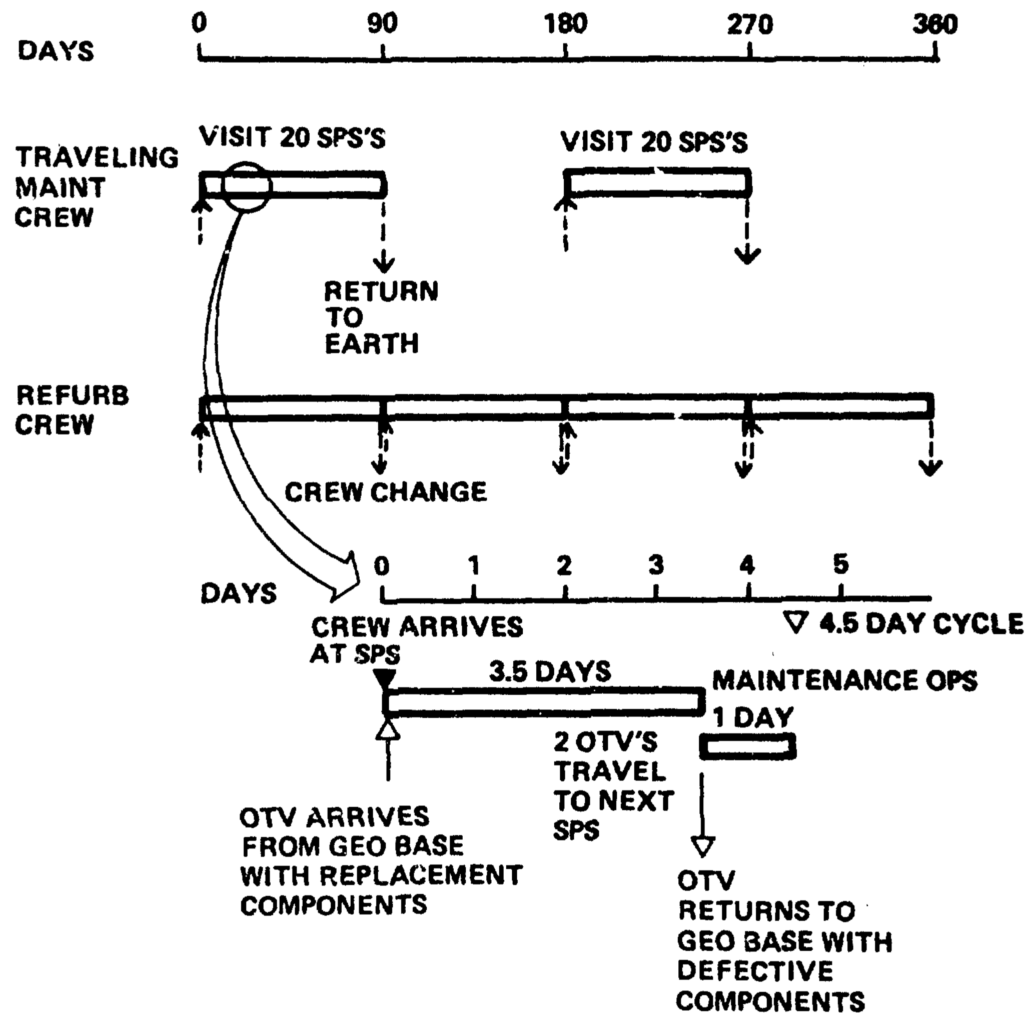
SPS MAINTENANCE TIMELINE

The top-level timeline, shown in the figure, shows that there are two types of operations: 1) maintenance operations at the satellite, and 2) refurbishment of defective components at the GEO base.

The at-satellite maintenance occurs over a 90 day period when each satellite is visited by a mobile maintenance crew and equipment for a 3.5 day staytime. Twenty operational 5 GW SPS's are assumed in the mission model. At the end of the 90 day period, the traveling maintenance crews are returned to Earth. They return to orbit after 90 days on Earth and then repeat the maintenance visit routine. Hence, each satellite is visited twice a year for maintenance. The refurbishment operations are conducted continuously with a crew changeout every 90 days.

SPS Maintenance Timeline

SPS-2716

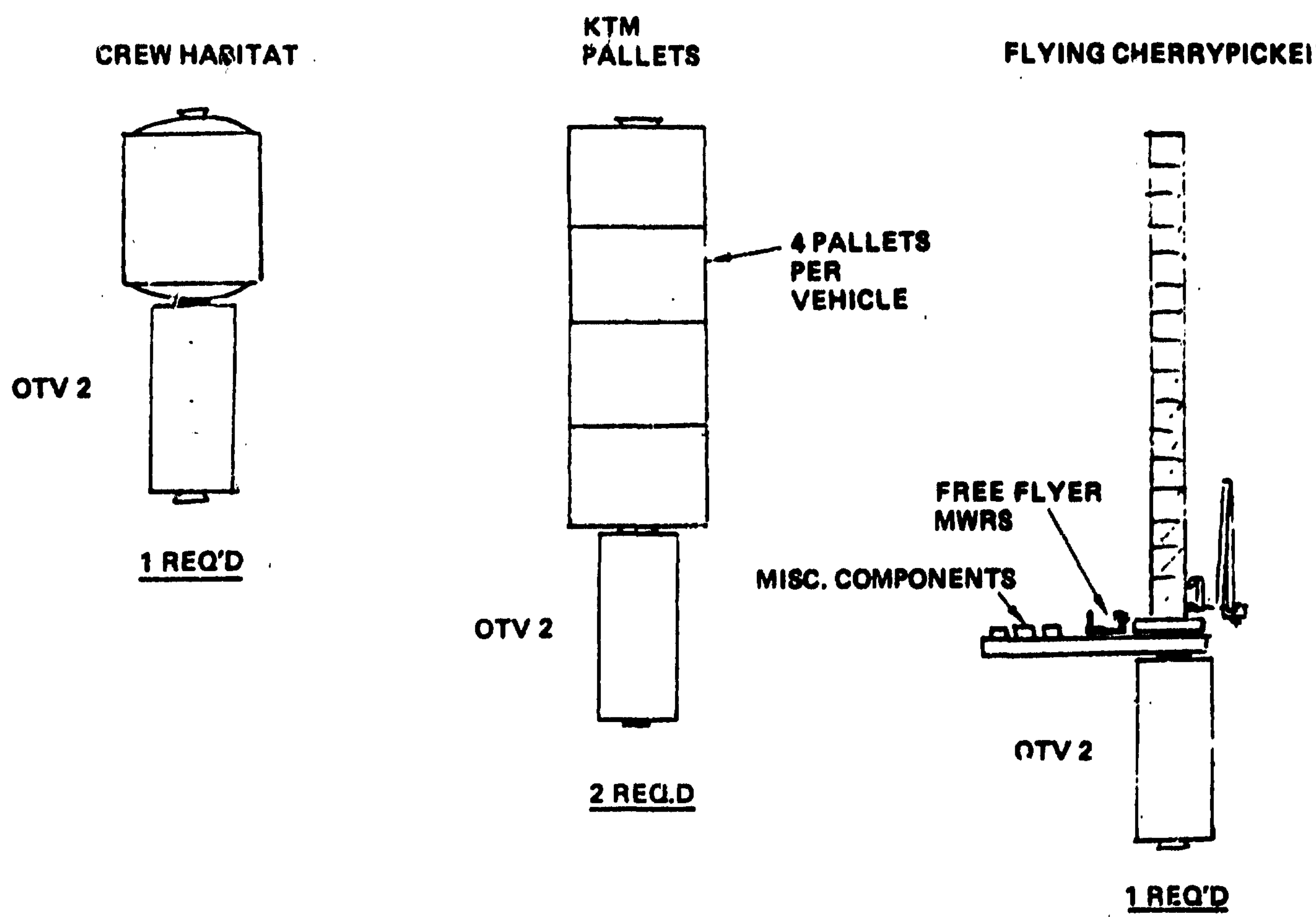


SPS MAINTENANCE TRANSPORTATION VEHICLE FLEET

This figure shows the vehicles that are used by the Mobile Maintenance Crew during their 90 day tour of the SPS's.

The crew habitat and the Flying Cherrypicker OTV's make the entire 90 day tour before returning to the GEO Base. The KTM Pallet Vehicles shuttle back and forth between the satellites and the GEO Base delivering defective and refurbished Klystron Tube Modules (KTM's).

SPS Maintenance Transportation Vehicle Fleet



SPS FAILURE SUMMARY - 5 GW SPS

Eighteen SPS components were selected for detailed maintenance analysis. The components were selected for one of three reasons: 1) they were a high failure-rate component, 2) failure of the component results in significant power loss, or 3) the component was representative of a class of components.

This Table shows the number of failures that are predicted for each SPS, the total for a 20 satellite fleet, and the monthly refurbishment rate required at the GEO Base.

SPS Failure Summary – 5 GW SPS

BOEING

SPS-2914

WBS	NOMENCLATURE	QTY/ SPS	FAILURES PER YEAR [3]	NO. OF FAILURES 6 MO.	NO. OF FAILURES 6 MO./20 SPS	NO. PER MONTH TO BE RECEIVED
1.1.1.1.4	BLANKET TENSIONING DEVICES	168,960	162.5	81.25 [1]	1625 [1]	[1]
1.1.1.3.2	BLANKET MECHANICAL ATTACHMENT	168,960	329 [2]	164.5 [2]	3290 [2]	[2]
1.1.1.4.5	CELL STRING BLOCKING DIODES	9,536	3.5	1.75	35	5.8
1.1.2.2.1	DC/RF CONVERTER MODULE (KTM)	101,552	3967	1983.5	39670	6612
1.1.2.3.2	SWITCHGEAR	456	4.5	2.25	45	7.5
1.1.2.3.3	DC/DC CONVERTER (POWER PROCESSORS)	228	12	6	120	20
1.1.2.3.4	DISCONNECT SWITCHES	453	1.5	.75	16	2.7
1.1.2.4.2	DC/DC CONVERTER THERMAL CONTROL	228	2	1	20	3.3
1.1.2.5.1	RECEIVERS	101,784	2	1	20	3.3
1.1.2.5.2	DIPLEXERS [4]	101,784	1	.5	10	1.7
1.1.2.5.3	PHASE TRANSMITTERS	110,204	14.5	7.25	145	24.2
1.1.2.5.4	PHASE RECEIVERS	110,204	2	1	20	3.3
1.1.2.5.5	CONJUGATORS	101,784	16.5	8.25	165	21.5
1.1.2.5.6	CABLING	109,444	12.5	6.25	125	20.8

[1] FAILURES COULD BE TOLERATED—NO MAINTENANCE PLANNED
[2] REDESIGN PART TO ELIMINATE FAILURES
[3] BASED ON DATA FROM PHASE I ANALYSIS
[4] A COMPONENT THAT WOULD BE AN INTEGRAL PART OF THE KLYSTRON TUBE MODULE

WBS 1.1.1.4.5 - CELL STRING BLOCKING DIODES MAINTENANCE ANALYSIS DATA

This chart shows a sample of the level of maintenance detail that was developed for each of the selected components.

SPS-2743

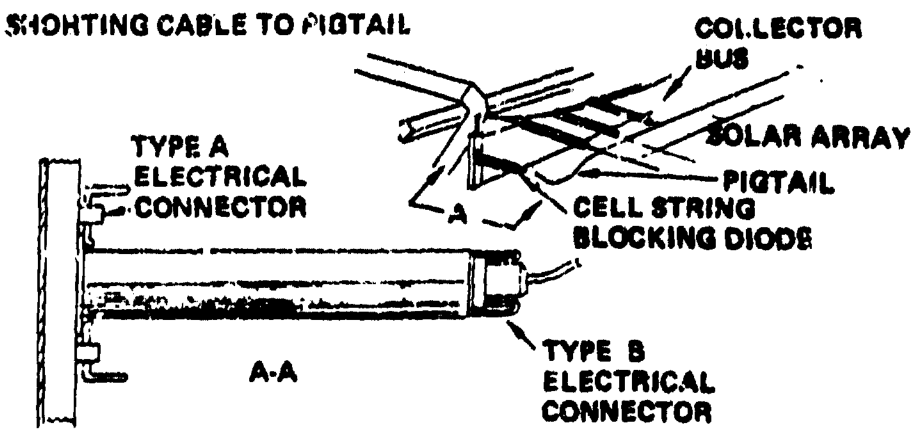
WBS 1.1.1.4.5—Cell String Blocking Diodes Maintenance Analysis Data

FAILURE RATE: 3.5 PER YEAR, 1.75 PER 6 MONTHS

FAILURE MODES	FAILURE EFFECT	HOW DETECTED
DIODE OPEN CIRCUIT	NO CURRENT FROM STRING	FAULT ANNUNCIATOR AT STRING CURRENT MONITOR
DIODE SHORT CIRCUIT	SAME	SAME

MAINTENANCE PROCEDURE

STEP	OPERATION	TOOLS
1	ATTACH SHORTING CABLE TO FAR END OF STRING	SHORTING CABLE
2	DEPLOY SHORTING CABLE TO NEAR THE DEFECTIVE BLOCKING DIODE	
3	IF THE DIODE IS OPEN CIRCUITED ATTACH SHORTING CABLE TO PIGTAIL	
4	DISCONNECT PIGTAIL	
5	IF THE DIODE IS SHORT CIRCUITED, ATTACH SHORTING CABLE TO PIGTAIL	
6	DISCONNECT DIODE CANNISTER FROM POST	
7	INSTALL REPLACEMENT DIODE CANNISTER	
8	ATTACH PIGTAIL CONNECTOR	
9	DETACH SHORTING CABLE	



REMARKS

THE DEXTROUS MANIPULATORS WILL BE OPERATING AROUND A "HOT" BLANKET. INSULATED END EFFECTORS IS THE LEAST AMOUNT OF PROTECTION THAT SHOULD BE PROVIDED.

SOLAR COLLECTOR TOP SURFACE MAINTENANCE ACCESS SYSTEM

The fundamental premise in the maintenance access systems analysis was that every SPS component (except structural members) must have a maintenance equipment access provision (even those components which have a negligible failure rate). It was deemed prudent to force this requirement so that unexpected failures could be attended to.

It was found that there were 10 general maintenance access requirements. It turns out that these 10 access requirements can be satisfied by combinations of built-in tracks, a flying cherrypicker, a rotary boom, and some gantries.

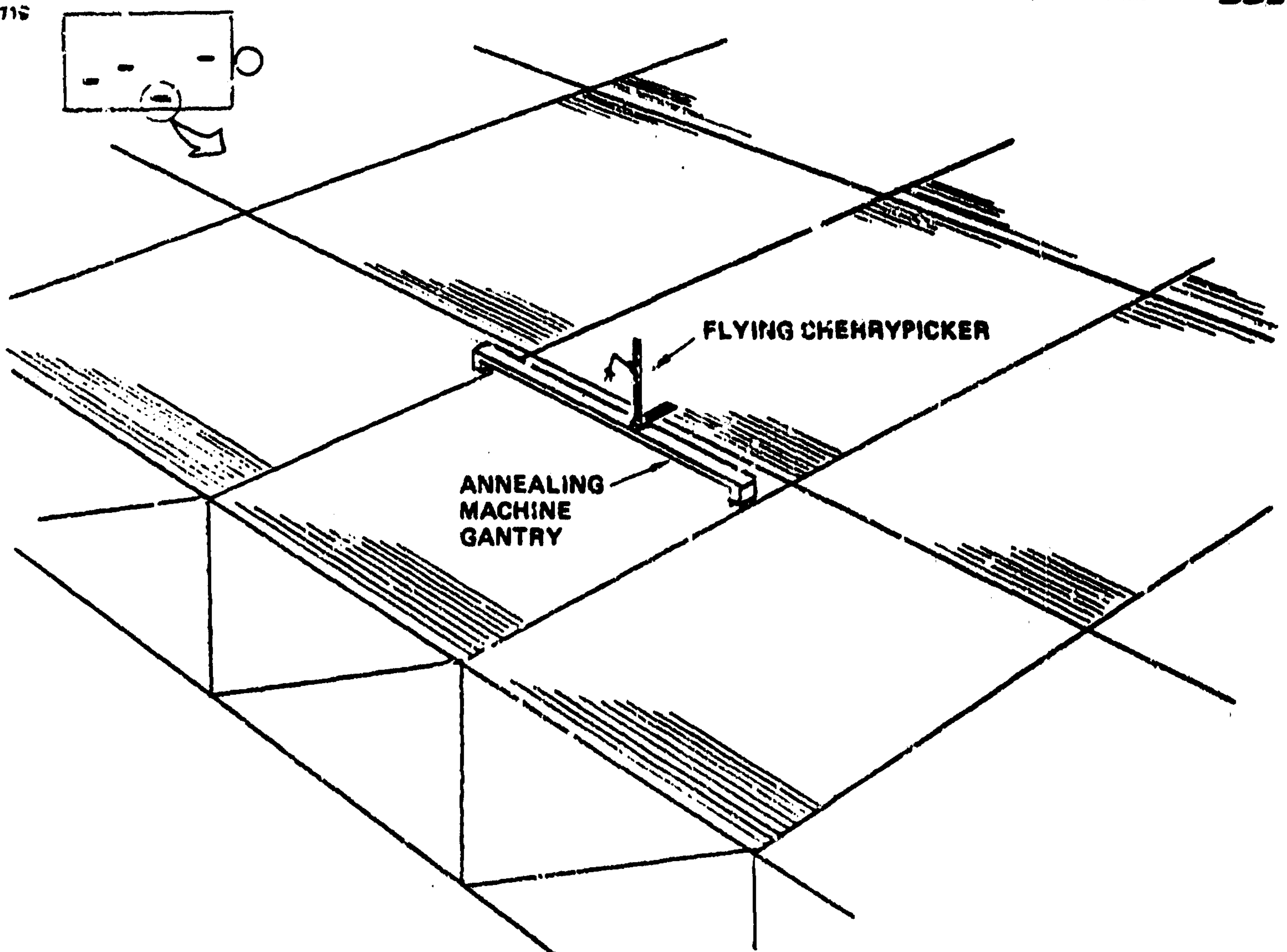
Solar Array Top Surface Access Systems

The baseline satellite has a requirement for some solar array annealing machines (WBS 1.1.1.6) which would be mounted on gantries which can traverse over the top surface of the solar collector. There are four of these gantries that operate on a built-in track network on the satellite. These gantries and tracks provide a ready-made maintenance access system for getting to the entire upper surface of the solar collector. It will be necessary to get a maintenance cherrypicker onto the gantries to perform maintenance on the solar array components (tensioning devices, catenary cables, and cell string blocking diodes).

This Figure illustrates the concept. A flying cherrypicker would rendezvous with a gantry to which is attached a flying cherrypicker carriage. This carriage has a docking interface to which the cherrypicker would mate. This carriage would then traverse across the gantry as required. A flying cherrypicker was employed as there are not enough maintenance tasks to warrant the expense of a permanent cherrypicker installed on each gantry.

Solar Collector Top Surface Maintenance Access System

SPS-2716



THE FLYING CHERRYPICKER

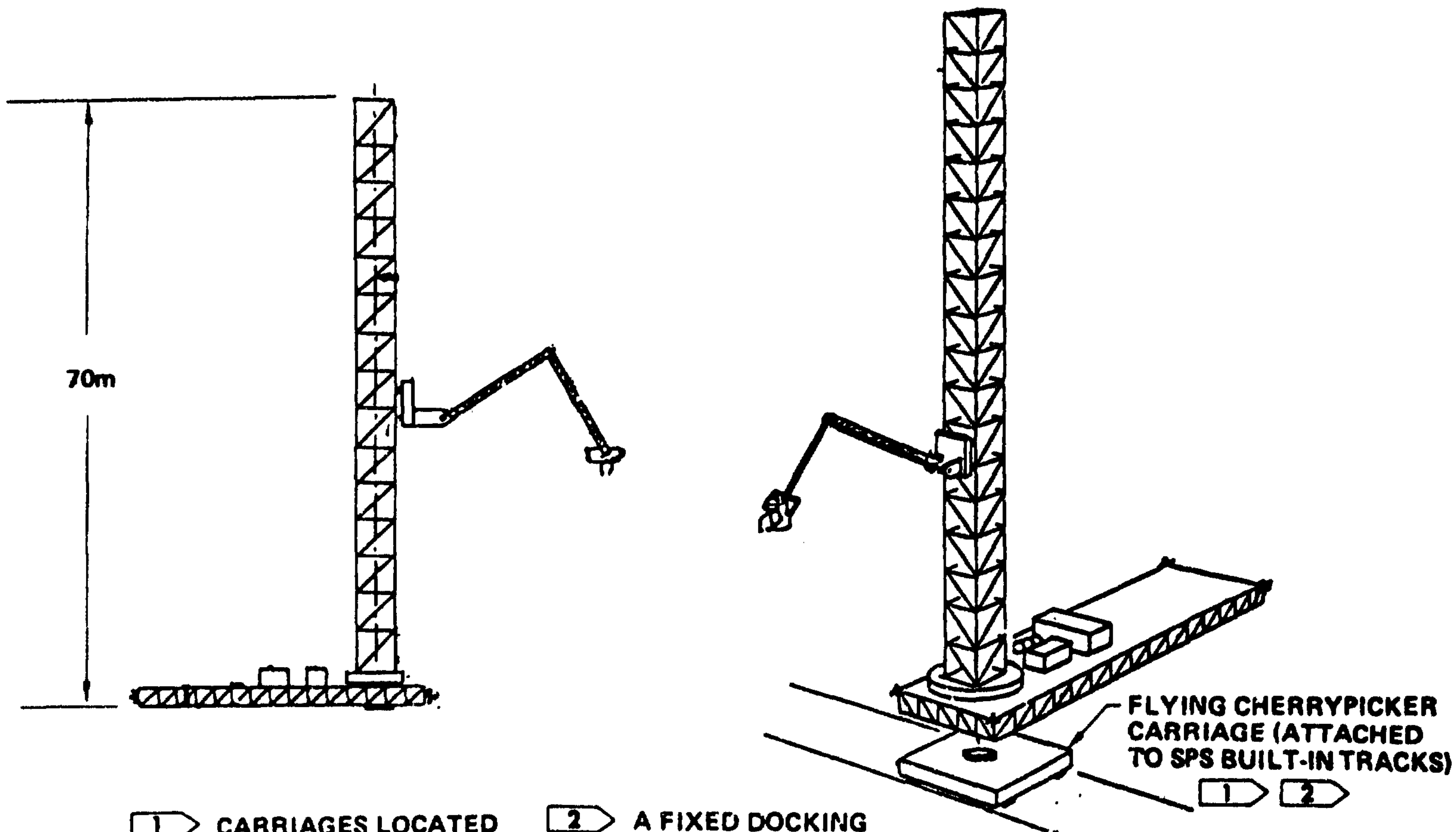
The maintenance access concepts all use a machine that has been dubbed "the flying cherrypicker." The figure illustrates the concept. The primary reason that this machine concept was created was that the predicted failure rates of the components to be serviced was much too low to warrant dedicated maintenance cherrypickers. Also, due to the complexities of the various locations in which cherrypickers would be required, it was not feasible to create an integrated track network that would allow a track-mounted cherrypicker to get to all of the locations. Hence, a flying cherrypicker and a set of track-mounted carriages were created.

The flying cherrypicker carries along a power supply which would be connected to the carriage after docking. The platform on the flying cherrypicker is used to transport the replacement components, the components that were removed from the satellite, and the maintenance tools. A docking port for a free-flyer is also provided on the platform. This provides a location for transporting the free-flyer on the inter-satellite flights.

Examination of the failure rate data shows that there would be about 12 components to be serviced by the flying cherrypicker during a bi-annual maintenance visit (2 cell string blocking diodes, 2 to 3 antenna switchgear, a DC-DC converter, a disconnect switch, and a DC-DC converter thermal control system.) During the 52.5 hours of available work time there would be sufficient time available for one flying cherrypicker to perform the changeout of these devices.

Flying Cherrypicker

SPS-2778 A



1 CARRIAGES LOCATED ON ANNEALING MACHINE GANTRIES

2 A FIXED DOCKING PLATFORM LOCATED ON EACH ATTITUDE CONTROL SYSTEM SUPPORT ARM

MOBILE MAINTENANCE OPERATIONS

A crew of 83 people, see figure, are loaded into a mobile crew habitat at the GEO base and are transported to the operational SPS's using an OTV.

The crew habitat docks to a docking port on the satellite's antenna. The satellite will have been deactivated from the ground just prior to the arrival of the crew. The mission control center on the ground will have accumulated a detailed listing of most of the faulty satellite components. A detailed operating plan will have been concocted to plot the maintenance crew's activities while at the satellite so that a minimum of wasted motion is incurred. Upon arrival, a two-man free-flyer vehicle will be dispatched to make a flyover of the satellite to detect non-annunciated failures, e.g., solar array tensioning device failures.

The replacement component cargo OTV docks to a transporter located on the antenna and drops off a pallet of KTM's. It will then fly to another antenna-attached transporter to drop off another load of KTM's. There are four places to do this.

The maintenance crews are taken from their crew habitat to maintenance gantries located on the antenna using a crew bus that is stationed on the antenna. There are 22 maintenance gantries on the antenna. The KTM pallet transporter is moved about to locations where racks of KTM's can be offloaded onto the maintenance gantries.

The maintenance gantries move to predesignated locations where the cherrypicker then removes defective KTM's and replaces them with good ones.

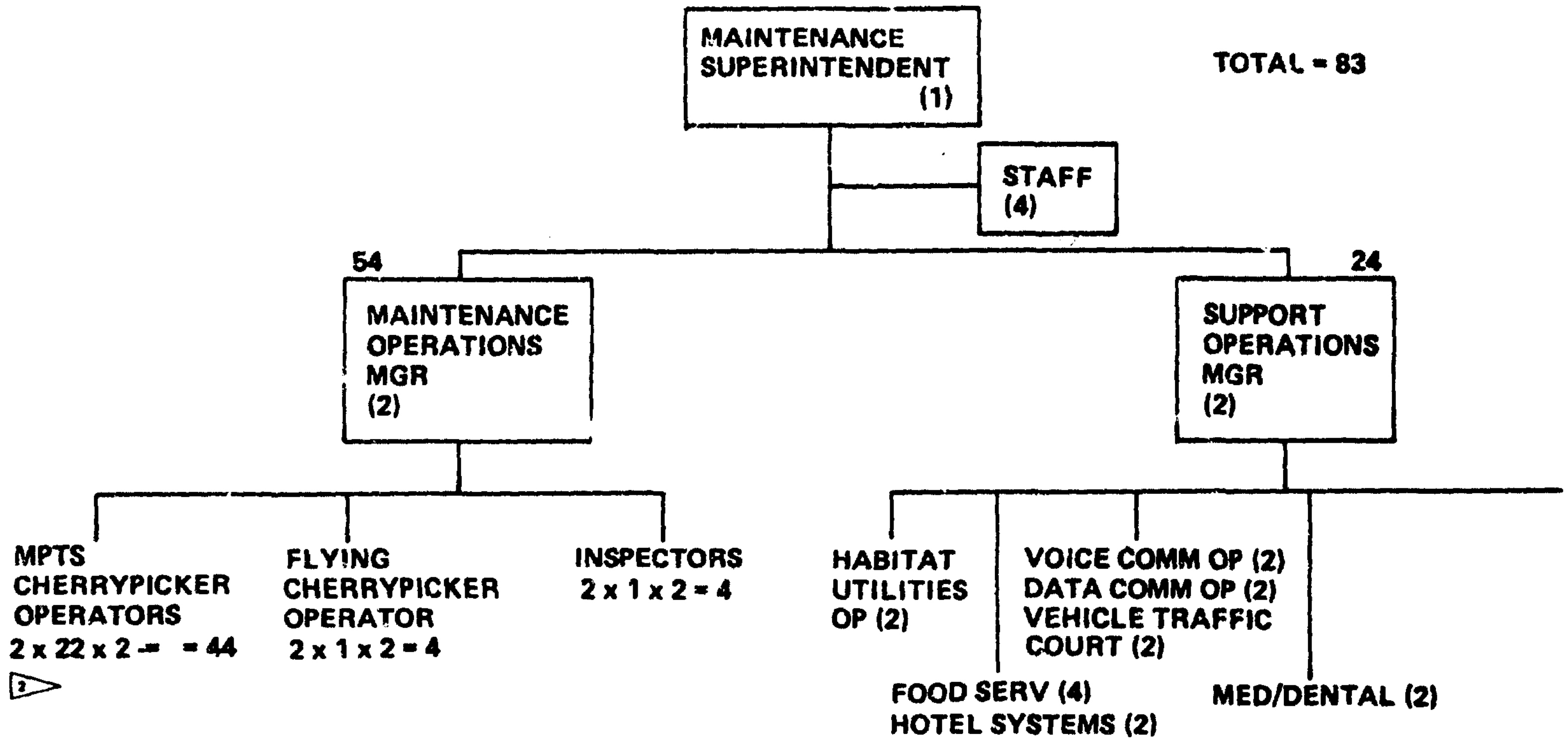
(Continued)

Meanwhile, the flying cherrypicker is manned, the replacement components loaded onto it, and then it flies to docking carriages located in various locations in the satellite. The cherrypicker removes defective components and replaces them with good ones.

These operations continue for two shifts a day for 3 1/2 days. The crew habitat and flying cherrypicker then moves on to the next satellite where they will be met with an OTV loaded with replacement parts. The defective components are returned to the GEO base where they will be refurbished.

Mobile Maintenance Crew

SPS-2728



[1] NUMBER IN ( ) INDICATES NO. OF PEOPLE REQ'D TO STAFF THIS JOB OVER 2 SHIFTS

[2] (NO. OF OPERATORS PER SHIFT) × (NO. OF MACHINES) × (NO. OF SHIFTS) = TOTAL NO. OF PEOPLE REQ'D TO STAFF THIS JOB OVER 2 SHIFTS

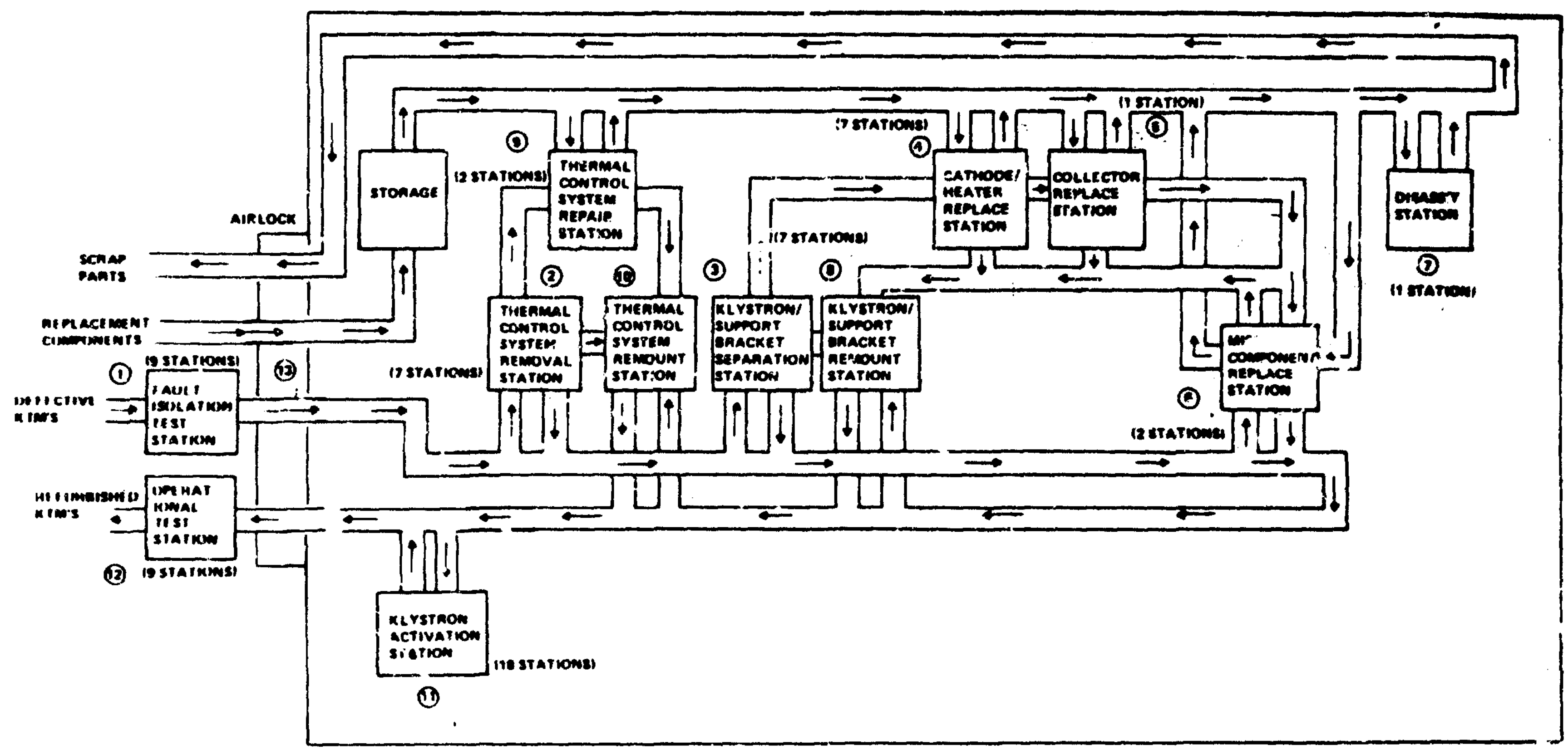
KLYSTRON TUBE MODULE REFURBISHMENT OPERATIONS

The refurbishment operations requirements for each of the selected components were examined. The Klystron Tube Module was by far the driving requirement due to the large quantity of units to be refurbished each month and the complexity of the units.

This Figure shows the production line required to process the KTM's. This production line is shown incorporated into a Maintenance Module at the GEO Base.

Klystron Tube Module Refurbishment Operations

SPS-2762



DEFECTIVE COMPONENTS SENT TO STATION 7 FOR POSSIBLE RECLAMATION OF USABLE PARTS

NO SCALE

SATELLITE MAINTENANCE CREW AT THE GEO BASE

This Table summarizes the maintenance crew size located at the GEO Base.

Satellite Maintenance Crew at the GEO Base

SPS-2750

KLYSTRON TUBE REFURB	PER SHIFT	TOTAL FOR 2 SHIFTS	
SUPERVISION	(6)	(12)	
REFURB OPERATIONS	(109)	(218)	
FAULT ISOLATION TEST	18		
THERMAL CONT	18		
BRACKET HANDLING	14		
KLYSTRON REFURB	8		
MISC COMPONENT REFURB	4		
SCRAPPING	1		
KLYSTRON ACTIVATION	36		
OPERATIONAL TEST	9		
STORES	1		
MISC. COMPONENT REFURB			
SUPERVISION	(1)	(2)	
REFURB OPERATIONS	(12)	(24)	1 DOES NOT INCLUDE SUPPORT PERSONNEL (HOTEL, FOOD SERVICE, ETC.). THESE WILL BE ACCOUNTED FOR AT THE GEO BASE LEVEL
DISASS'Y/ASS'Y	4		
MECH DEVICES	2		
ELECTRICAL DEVICES	2		
ELECTRONIC DEVICES	2		
SYSTEM TEST	2		
PALLET LOADING/OFFLOADING AND STORAGE			
CHERRYPICKER OPERATORS	(2)	(4)	
TOTAL	130	260 1	

SATELLITE MAINTENANCE SUPPORT PROVISIONS AT THE GEO BASE

The maintenance analysis established the requirements for two maintenance modules and their associated support equipment and crew. To integrate these systems into the GEO base, it is necessary to add the maintenance vehicle docking and handling provisions, and the payload handling provisions, and the track system that intertwines these areas into the GEO base track network. In addition, it will be necessary to add three crew habitat modules for housing the maintenance crew. The figure shows the various elements that have to be integrated into the GEO base.

Maintenance OTV Docking Systems and Operations

Requirements for four maintenance OTV's has been established. At the GEO base, provisions must be made for docking of each vehicle plus provisions for parking the payload.

A total of eight docking ports are required. Every 4 1/2 days, an OTV with KTM pallets will be launched from the GEO base and another OTV will be incoming from a satellite. Stacking/unstacking the pallets on/off the OTV's will require a 90 m cherrypicker working one shift per day. This cherrypicker would also be used for a few days once every 90 days when the traveling maintenance crew returns to the base. This maintenance OTV area would be integrated into the POTV and cargo tug docking area required to support the satellite construction operations.

Pallet Loading/Unloading and Storage Area

A dedicated pallet loading/unloading and storage area with some support equipment will have to be provided.

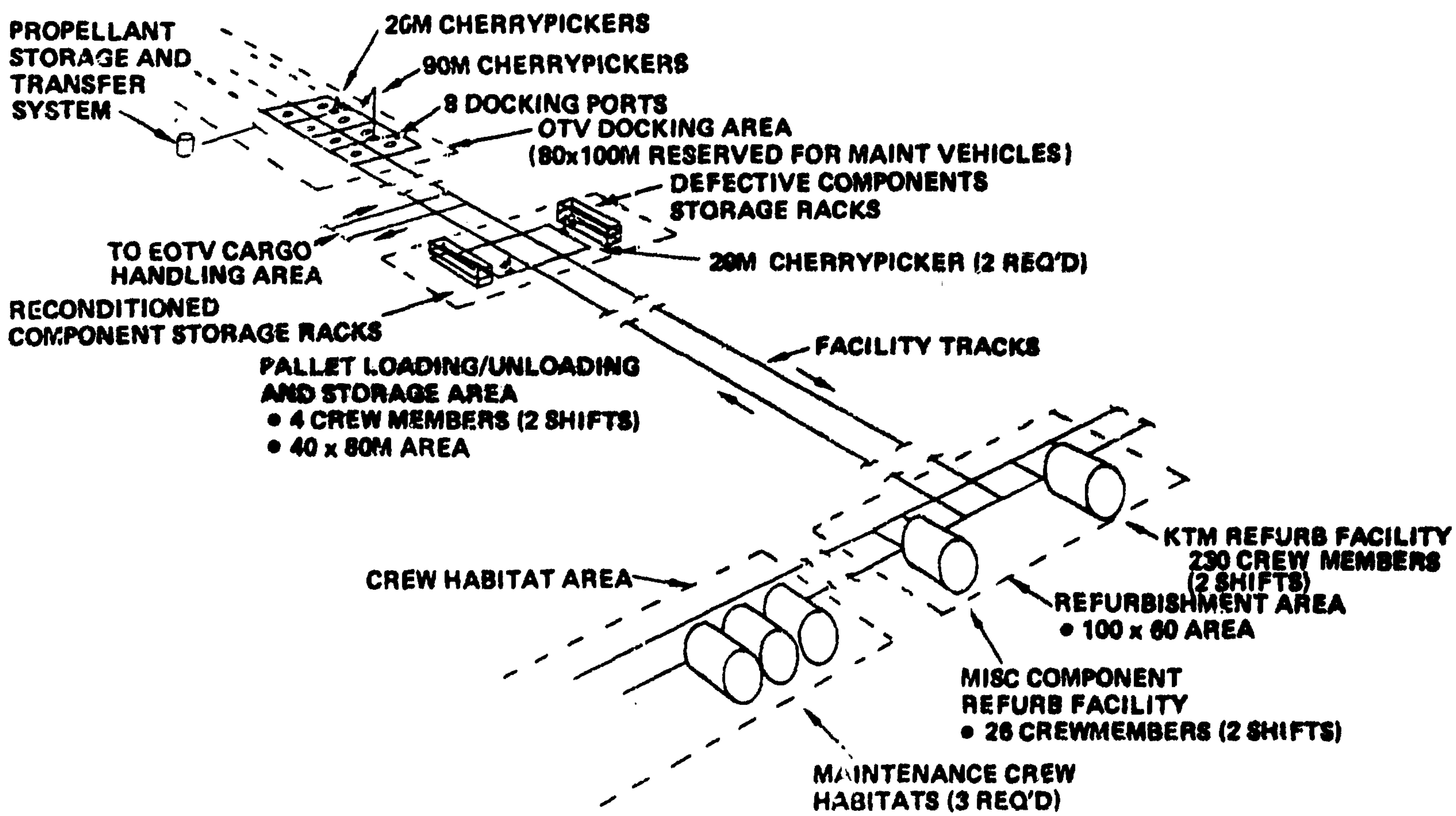
The cargo pallets will be offloaded from the OTV and transported to the handling area on cargo transporters. A pair of 20 m cherrypickers will unload the KTM racks from the pallet and will move them to a defective KTM storage area.

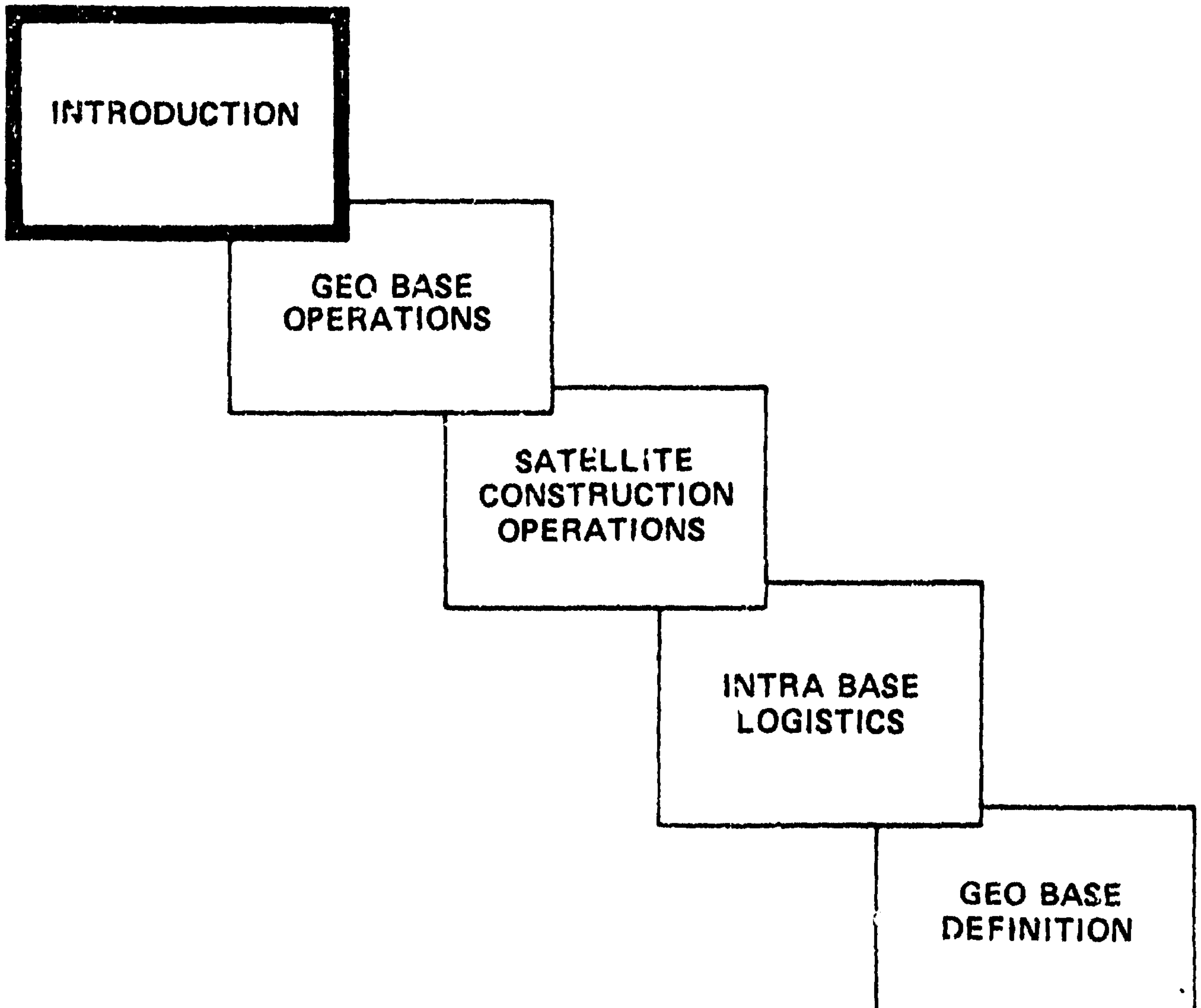
When a load of defective KTM's are required at the KTM refurbishment area, the cherrypickers will load up a transporter with the racks of a defective KTM's. This transporter hauls these units over to the facility where the KTM's are individually removed from the racks for processing.

As reconditioned KTM's emerge from the processing line, they are loaded into the racks that were liberated when defective components were removed. When a complete load of reconditioned KTM's are ready, the transporter moves back to the Pallet/Loading Offloading and Storage Area. The racks are placed into storage.

Satellite Maintenance Support Provisions at the GEO Base

SPS-2723





GRUMMAN

1079-001D

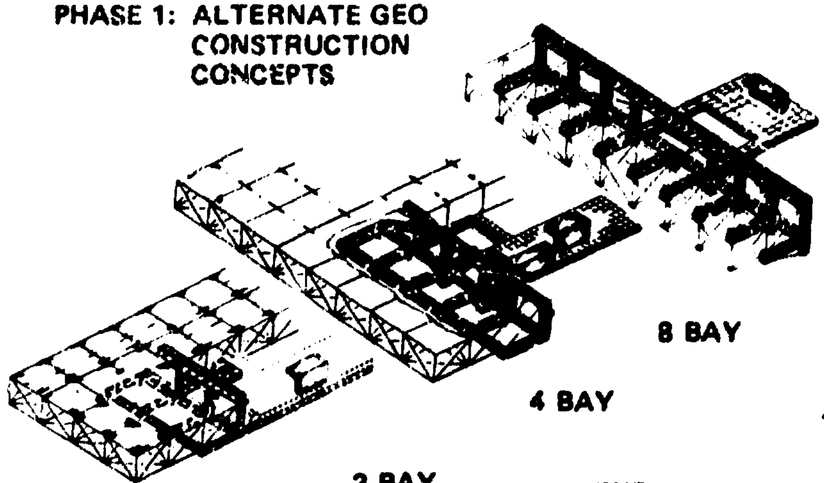
SPS SYSTEM DEFINITION STUDY FOR BOEING/JSC

Different methods for constructing the 5000 MW reference satellite in GEO were investigated during Phase 1 by a joint Boeing/Grumman team. Alternate end builder construction concepts were developed by Grumman for direct comparison with a single-deck construction platform concept. These construction options are shown on the facing page.

Ground rules for preliminary analysis of the platform type and end builder construction concepts were to use a common antenna construction facility, and to constrain SPS final assembly and checkout to one satellite every six months. All options were evaluated in terms of cost, performance, complexity, risk, etc. The 8 bay wide end builder exhibited the highest unit cost and was not able to fully utilize its production capability. The comparison of the multi-pass end builder and the single-deck platform concepts was nearly even. The 4 bay end builder was selected, however, for additional definition work in Phase 2 because of its greater production rate growth capability.

SPS SYSTEM DEFINITION STUDY FOR BOEING/JSC

PHASE 1: ALTERNATE GEO CONSTRUCTION CONCEPTS



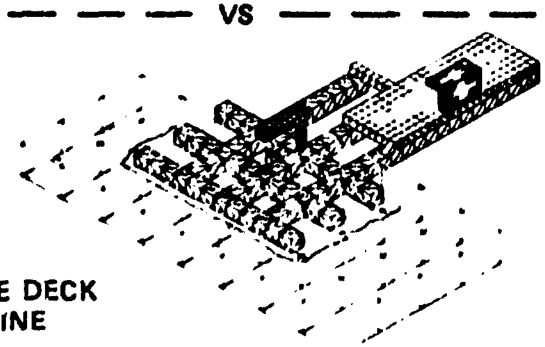
8 BAY

4 BAY

2 BAY

END BUILDERS

VS



SINGLE DECK BASELINE

PHASE 2: CONSTRUCTION BASE OPERATIONS & DEFINITION

4 BAY END BUILDER

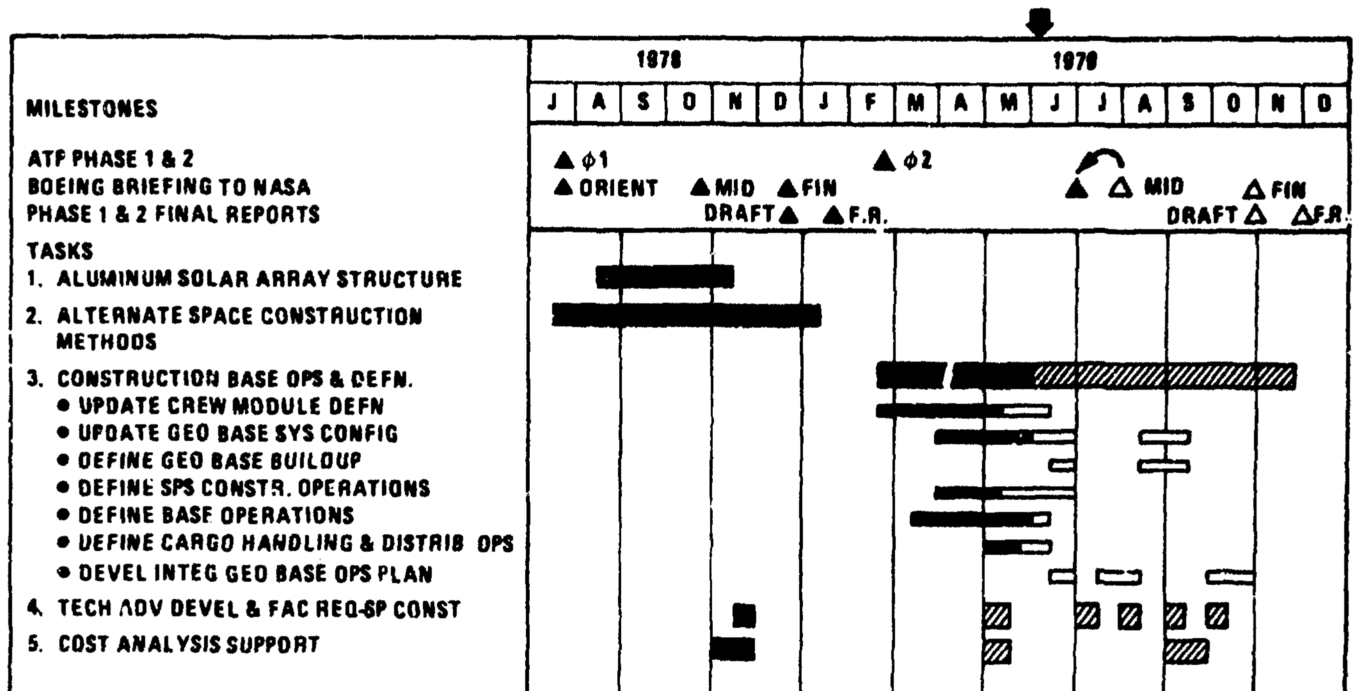
GRUMMAN

GRUMMAN SPS SYSTEM DEFINITION STUDY SCHEDULE

Grumman's Phase 2 effort for Boeing is focused on further defining the operations and systems elements of the 4 Bay End Builder. The major operations tasks include the analysis and definition of GEO Base Operations, SPS Construction Operations and intra-base cargo handling and distribution operations. Analysis of these functional areas will help to establish system feasibility and provide a basis for subsequent design updating. It also serves as a tool for identifying technology issues which require further study and/or near-term technical development. Work is currently underway on this Task 3 activity, as shown by the schedule on the facing page. In addition, the Phase I crew module definition is being updated and the 4 Bay End Builder GEO base configuration is being updated to include all work support and crew support facilities.

After the mid-term briefing, concepts will be examined for implementing base buildup and the GEO base operations plan will be prepared. Recommendations on space construction technology development requirements will also be provided by Task 4. Task 5 will provide the supporting cost data as needed.

GRUMMAN SPS SYSTEM DEFINITION STUDY – SCHEDULE



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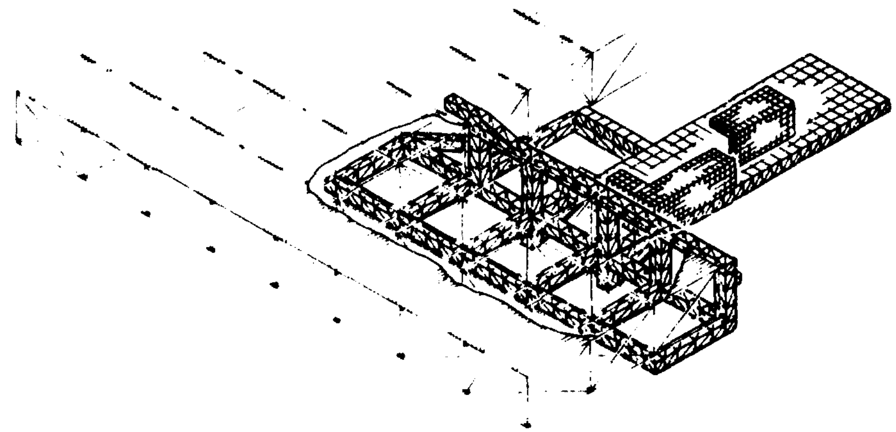
4 BAY END BUILDER BASE FEATURES (PHASE 1)

The main features of this base are shown on the facing page. The construction system characteristics, major equipments and their impacts on the satellite are listed.

4 BAY END BUILDER BASE FEATURES PHASE I



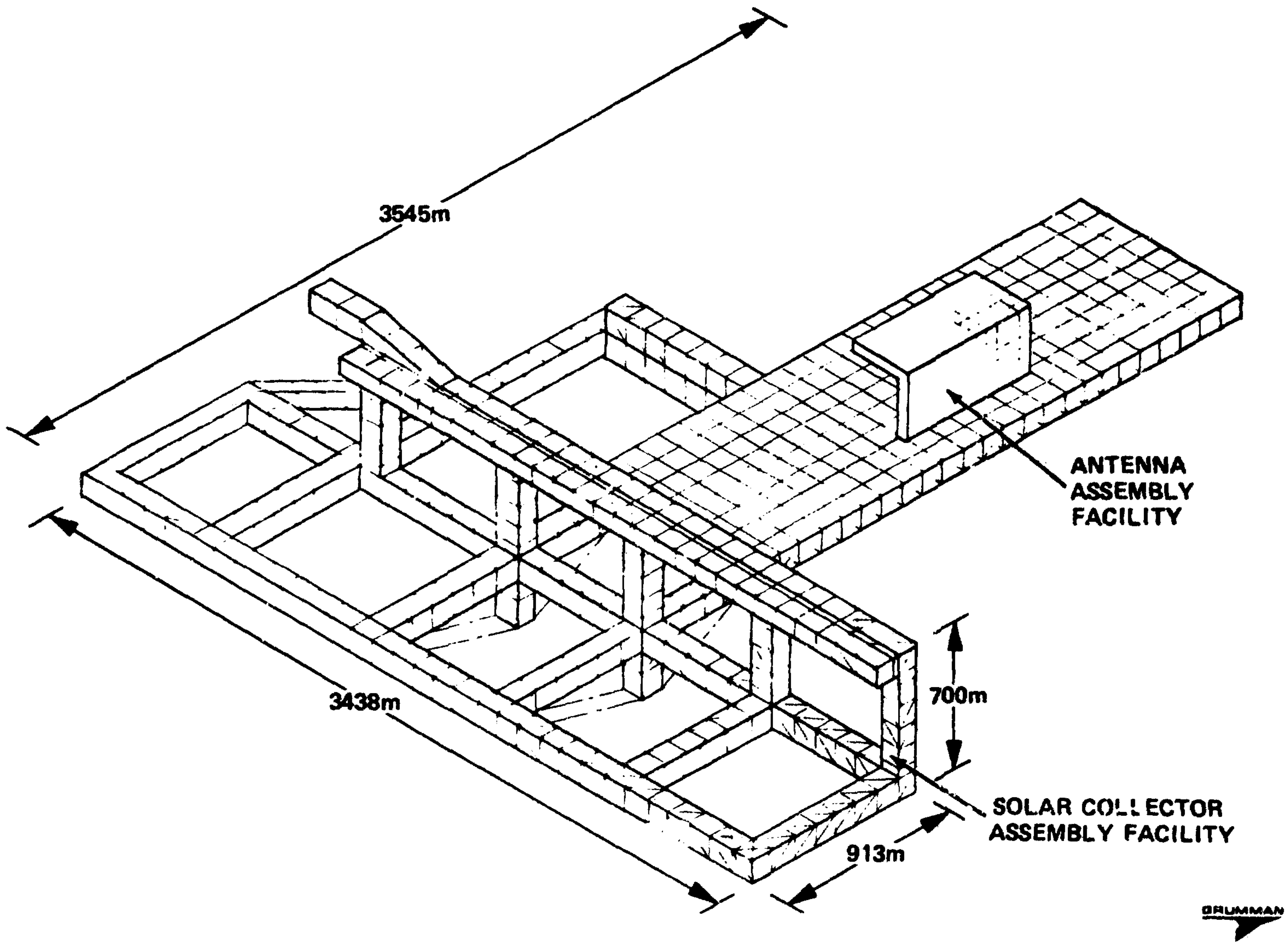
- MULTI-PASS CONSTR OF 8 X 16 BAY SPS
- CONSTR SYS
  - UNIT COST (1977\$) = \$9.07B
  - SIZE L x W x H = 3.68 x 2.96 x .70 km
  - MASS
    - o STRUCTURE = 2.93×10^6 kg
    - o TOTAL BASE = 6.37×10^6 kg
  - CREW TOTAL = 385
- ARRAY MODULE CONSTR. EQUIP.
  - BEAM MACHINES = 13
  - CRANE/C.P. = 11
  - INDEXERS = 7
  - BUS DEPLOYERS = 1
- SATELLITE DESIGN
  - SOLAR ARRAY ORIENTATION = LONGITUDINAL
  - LONGITUDINAL BEAMS = CONTINUOUS

GRUMMAN

4 BAY END BUILDER CONSTRUCTION BASE

The general arrangement of the SPS GEO construction base is illustrated on the facing page. The 3438 x 913 x 700 meter 4 bay end builder solar collector assembly facility is located at the forward end of the antenna facility.

4 BAY END BUILDER CONSTRUCTION BASE



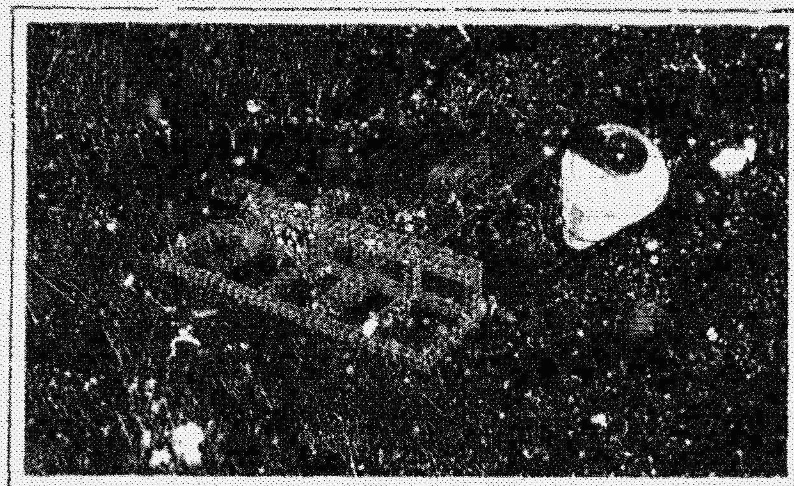
1079-019D

4 BAY END BUILDER CONSTRUCTION OPERATION

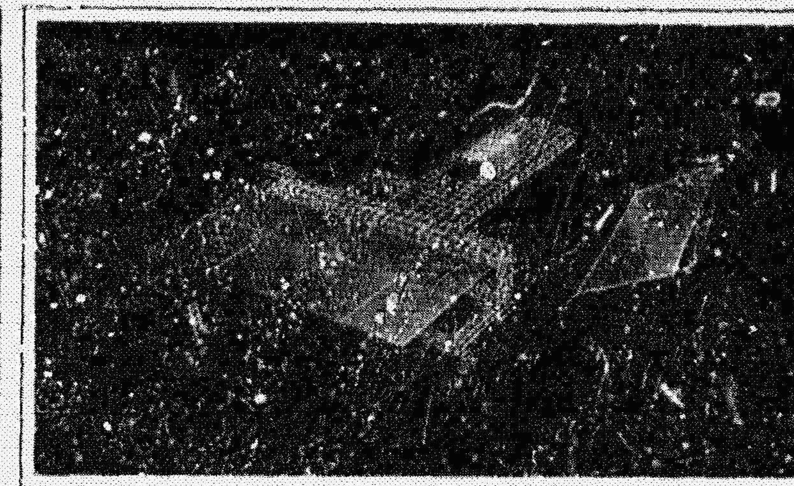
Construction of the 5000 MW reference satellite takes place in GEO. Consequently, the personnel needed to activate the 4 Bay End Builder Construction Base must travel first by means of the Shuttle to LEO and finally by means of an orbital transfer vehicle (OTV) which operates from the LEO base.

The 4 bay end builder assembles the SPS satellite in two successive passes as shown by the construction sequence illustrated on the facing page. During the first pass, the GEO construction base builds a 4 bay wide strip by 16 bays long. Construction of the satellite antenna is performed in parallel. When one-half of the satellite energy conversion system has been assembled, the base is indexed to the side and then back along the edge of the satellite. The base is realigned with the end frame of the satellite to start the second construction pass. The remaining 4 bay wide strip is attached directly to the assembled satellite systems as the base moves toward the other end. Large electric orbital transfer vehicles (EOTV) will deliver SPS materials and components throughout the assembly process. GEO base crews will also be rotated as needed. The satellite antenna is completed in parallel with the construction of the 8 x 16 bay energy conversion system. At the end of the second pass, the base is indexed sideward to mate the antenna with the centerline of the energy conversion system. Following the satellite final test and checkout, the base will be separated from the satellite and transferred to the next SPS GEO construction location.

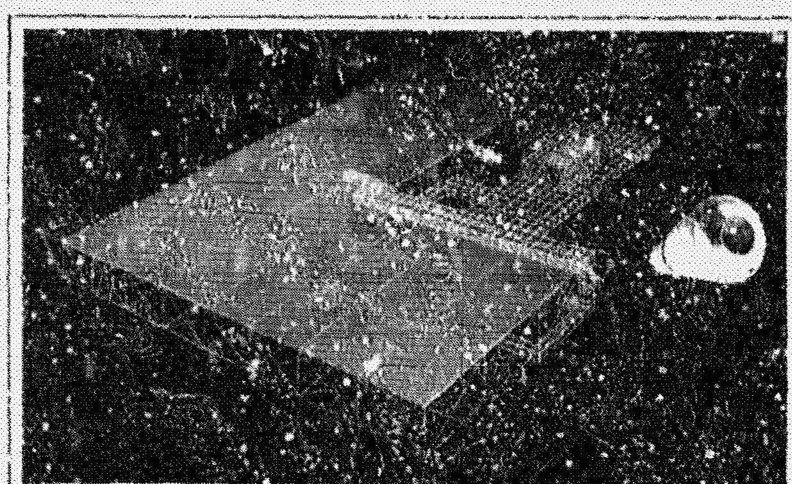
4 BAY END BUILDER CONSTRUCTION



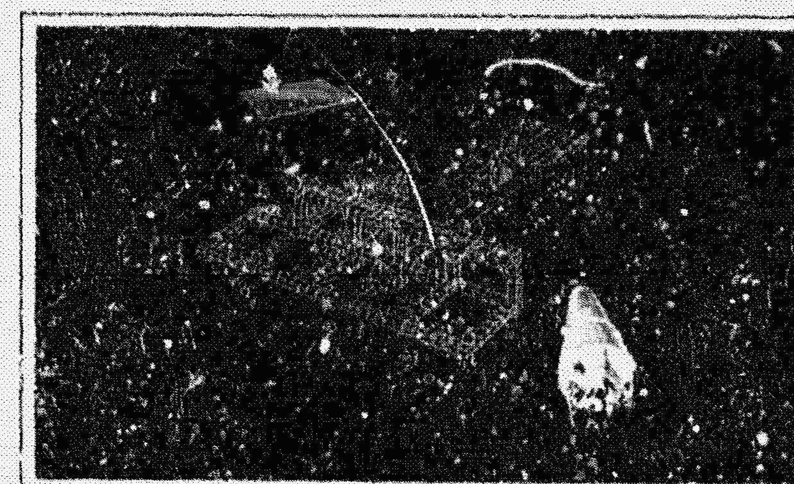
ACTIVATE BASE



FIRST CONSTRUCTION PASS



SECOND CONSTRUCTION PASS



CHECKOUT SPS & TRANSFER BASE

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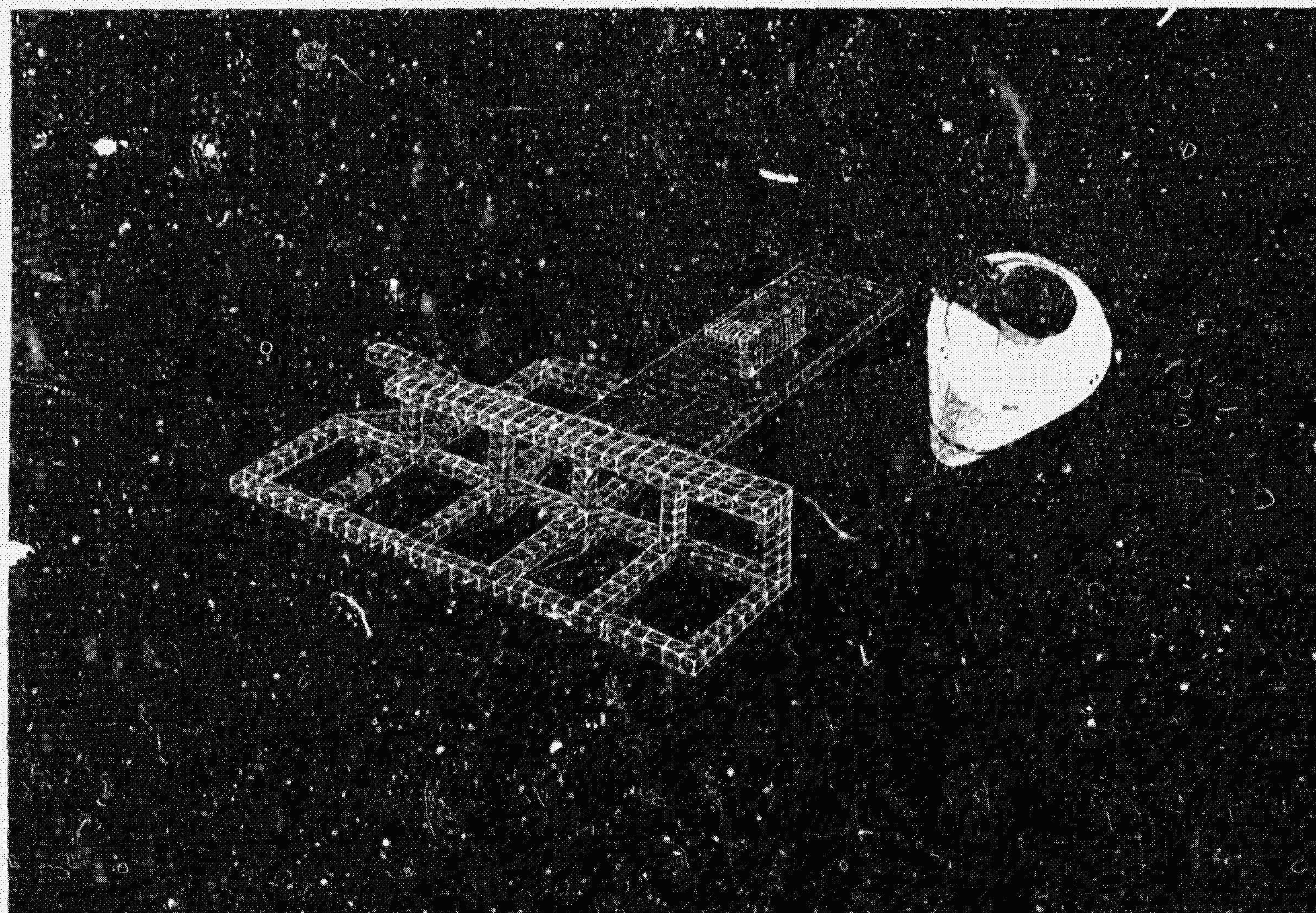
SPS CONSTRUCTION BASE ACTIVATION



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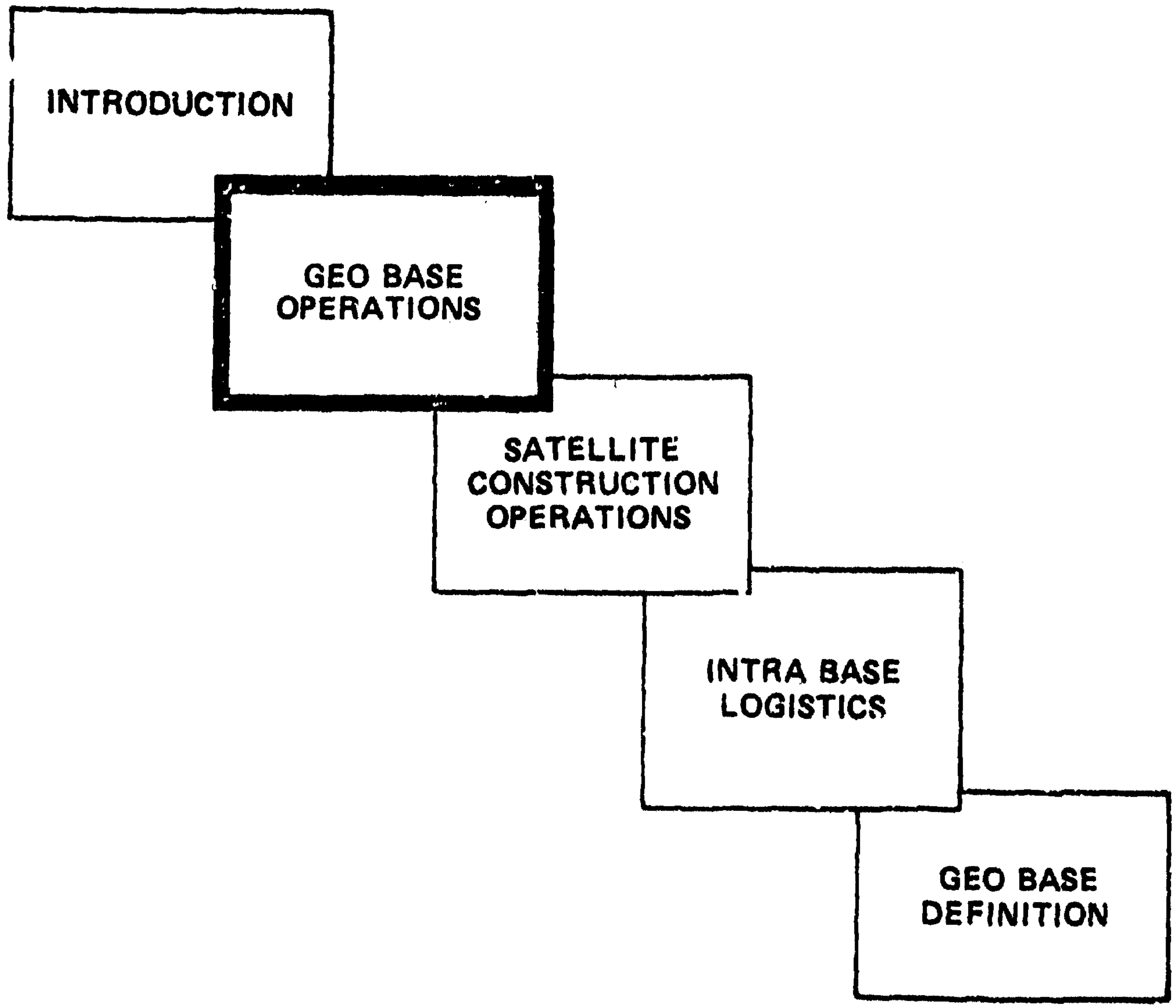
INTRODUCTION
GEO BASE OPERATIONS
SATELLITE CONSTRUCTION OPERATIONS
INTRA BASE LOGISTICS
GEO BASE DEFINITION

1079-002D

SPS GEO BASE OPERATIONS REQUIREMENTS & ISSUES

The SPS GEO construction base is used to build and commission two 5 GW reference satellites per year for 30 years. The GEO base is also required to support the maintenance activities on operational Solar Power Satellites and to service supporting elements of the SPS space transportation system (i.e., OTVs and EOTVs). The crew jobs and organizations for constructing and maintaining the SPS in GEO are defined in the Phase I Final Report Reference System Description (Volume III, D180-25037-3) and the Phase II Second Monthly Report (April 1979), respectively. The GEO construction facility includes many functions related to the operation of construction equipment, operation of base systems, and the support of crew operations. As the SPS reference system matures, all aspects of GEO base operations must be examined to verify system feasibility and identify areas needing further development. Several technology issues related to GEO base operations are listed on the facing page. While most of these issues are beyond the scope of the study, they include further analysis of required base functions, degree of automation, related crew functions and type of organization needed. Control of the diverse base functions is addressed below but it requires further study to size and cost, preliminary command and control systems. Other areas which require further study include: the impact of frequent crew rotation and related training requirements to maintain high productivity; crew habitability requirements for zero gravity versus artificial gravity plus related health, safety and rescue operational requirements for SPS construction; and operational limitations for IVA and EVA with required protection from ionizing radiation and other GEO environmental effects. In addition, base attitude control and required operational interfaces need further study.

SPS GEO BASE OPERATIONS REQUIREMENTS & ISSUES

- CONSTRUCT TWO 5GW SATELLITES PER YEAR FOR 30 YEARS
- SUPPORT OPERATIONAL SATELLITE MAINTENANCE
- SERVICE FLIGHT TRANSPORTATION VEHICLES
- GEO BASE PHASE 1 CREW JOBS & ORGANIZATION (D180-25037-3)
- SPS MAINTENANCE ORGANIZATION (APR '79 MPR NO. 2)
- GEO BASE OPERATIONS ISSUES
  - CREW FUNCTIONS & ORGANIZATION
  - COMMAND & CONTROL CONCEPT
  - CREW ROTATION & TRAINING POLICY
  - CREW HABITABILITY & HEALTH
  - CREW SAFETY & RESCUE
  - RADIATION PROTECTION & OTHER ENVIROMENTAL CONSTRAINTS
  - BASE ATTITUDE CONTROL
  - OPERATIONAL INTERFACES

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GEO BASE OPERATIONAL FUNCTIONS

The GEO Base performs three main functions:

- Construct solar power satellites (SPS)
- Service and maintain operational SPS
- Service flight logistic vehicles.

In order to accomplish these functions a number of others are imposed. The base must be capable of docking transportation vehicles, unloading them and then transporting supplies and personnel via a railroad system to work areas. Space workers require habitats that function in a manner similar to hotels, as well as pressurized enclosures that consist of control centers, cherry pickers and transportation vehicles. The construction and base equipment must be maintained and personnel health services must be provided. Because SPS construction will continue for many years, requirements exist for a continuing supply of new space workers. Therefore, training facilities must be provided. All of these functions are to be integrated into the Command and Control Organization.

GEO BASE OPERATIONAL FUNCTIONS

DIVERSE FUNCTIONS
TO BE INTEGRATED

CONSTRUCT SOLAR POWER SATELLITES
SUPPORT OPERATIONAL SPS MAINTENANCE
SERVICE FLIGHT TRANSPORTATION VEHICLES
CONTROL EXTERNAL LOGISTIC VEHICLES
DIRECT BASE TRANSPORTATION
MANEUVER BASE
CONTROL BASE SUBSYSTEMS
ASSURE CONSTRUCTION & MAINTENANCE QUALITY
OPERATE HABITATS
ASSURE CREW HEALTH & SAFETY
MAINTAIN BASE EQUIPMENT
PROVIDE COMMUNICATIONS & DATA
TRAIN CREW

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SPS GEO BASE OPERATIONAL INTERFACES

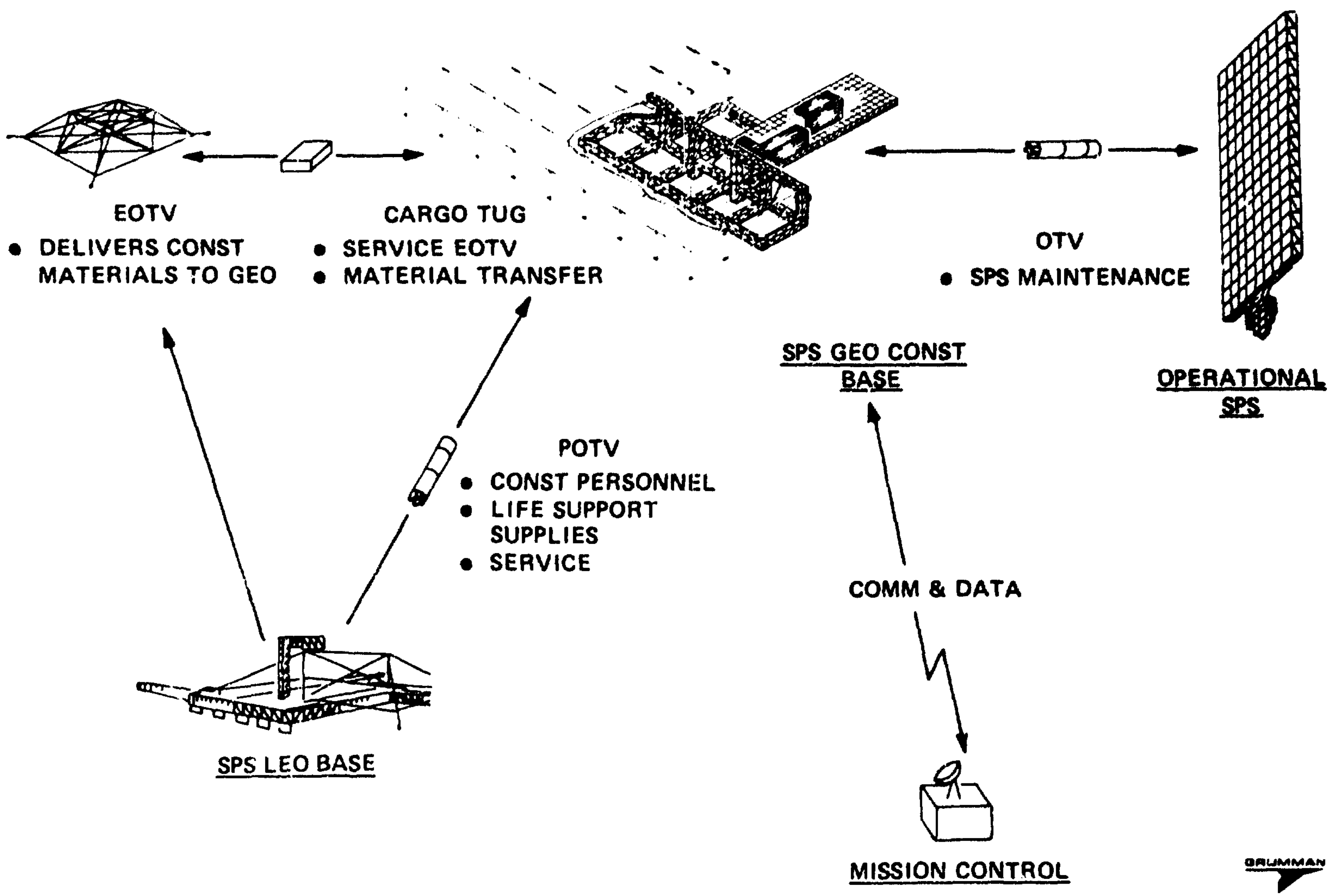
The illustration shows the GEO Base external operational interfaces. Earth mission control coordinates all aspects of SPS construction and operation. This includes all the ground and orbital elements. Construction progress, material and personnel needs are reported daily to earth mission control.

The GEO Base receives construction material via Electric Orbit Transfer Vehicles (EOTV). These vehicles are loaded at the LEO base, rendezvous with the GEO Base, and stationkeep while Cargo Tugs transfer material pallets. EOTV terminal rendezvous is coordinated by the GEO base Cargo Tugs require docking stations, cargo handling equipment and distribution/warehouses Service & maintenance crews transfer to the EOTV to perform solar array annealing operations.

Personnel and life support supplies are also shipped from the LEO Base utilizing Personnel Orbit Transfer Vehicles (POTV). These vehicles dock to the GEO Base, then crew transportation modules are attached for personnel unloading. Unloading equipment removes life support supplies and the POTV is serviced for return to LEO Base.

The GEO Base also prepares Orbit Transfer Vehicles (OTV) for the trip to service operational SPS. The GEO Base control center directs OTV departures and when the OTV's return, terminal control & docking are also coordinated by the GEO base. Base loading and unloading equipment, plus the necessary transportation/warehousing facilities, are required.

SPS GEO BASE OPERATIONAL INTERFACES



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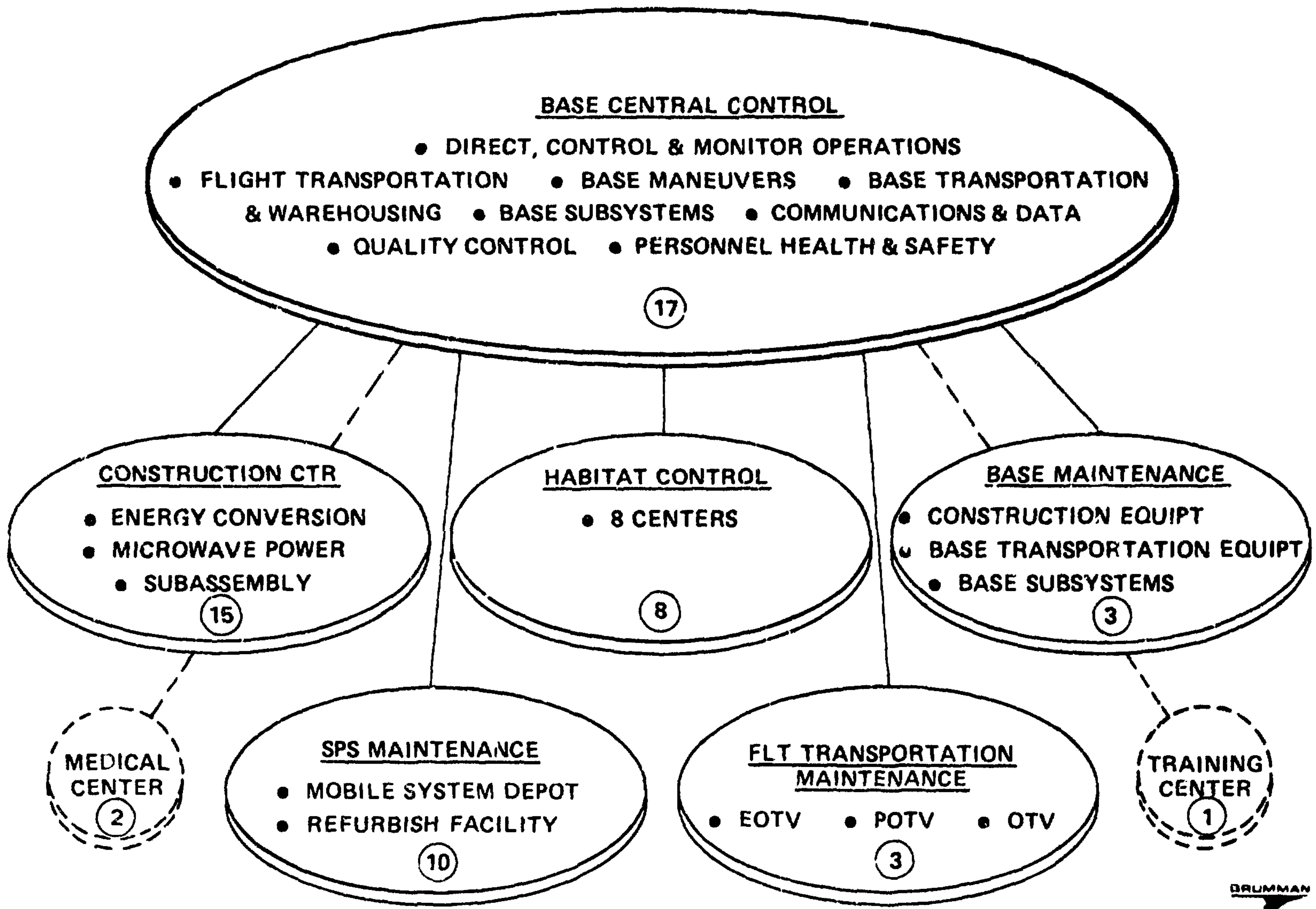
GEO BASE OPERATIONS CONTROL

The Base Central Control is where the Base Director, Construction Manager, Base Operation Manager and Base Support Manager are located. They direct and control all related GEO base operations and are supported by staff personnel who assist in planning, scheduling and monitoring base functions. Certain functions such as orbital control of the base, control of external and internal traffic, communications, data and base subsystems are handled directly from the Central Control Center. Other operational functions receive directions from the Central Control Center, but the interface for these functions (construction, habitat, base maintenance, SPS maintenance and flight transportation maintenance) could be performed at other locations.

The medical center is required for personnel well-being and is available should accidents or sickness occur. It is shown reporting directly to the Base Central Control and illustrated in broken lines as it is not primary for daily operations.

Training functions are also not required for day-to-day operations but are necessary for the base long term continuous operation.

GEO BASE OPERATIONS CONTROL



TOTAL PERSONNEL/SHIFT 59

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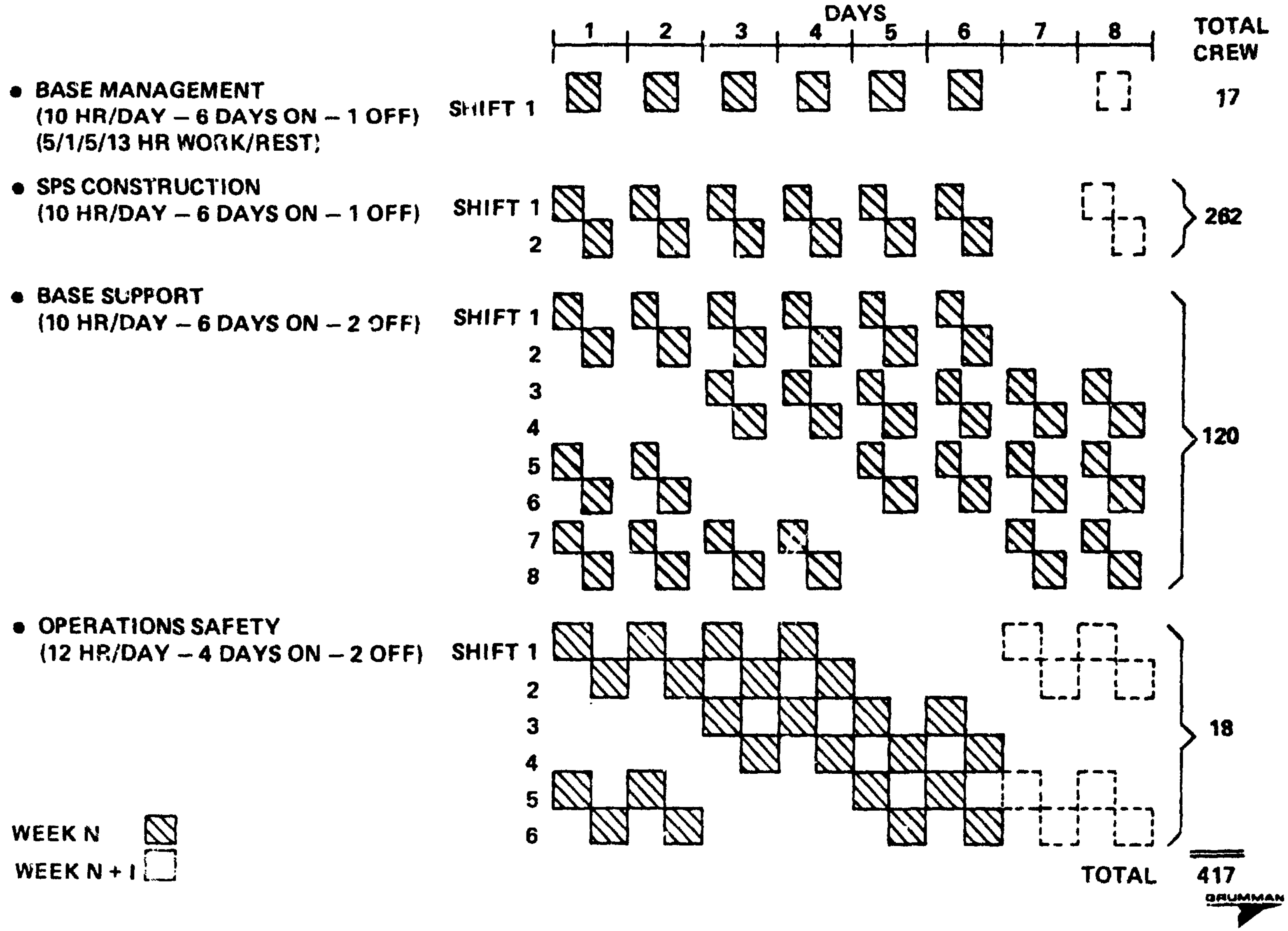
GEO CONSTRUCTION BASE CREW WORK SCHEDULE

Manning of the GEO Construction Base can be compared in some respects to manning an aircraft carrier at sea. Each system must accommodate several groups of people who are normally assigned to different activity schedules. The major operational activities include the single shift (on call) base management functions, the 20 hour/day – 6 day/week satellite construction operation, 7 day/week base support operations, and the 24 hour/day mission safety operations. Satellite and flight transportation vehicle maintenance support operations can also be included on the GEO Construction Base and follow similar activity schedule requirements.

Typical crew work-rest cycles that would satisfy the required activity schedule requirements are illustrated. Several shifts and different work-rest cycles are needed to satisfy the requirements for daily base support and around-the-clock mission safety coverage. For example, a 10 hour shift – 6 days/week with 2 days off allowed the base support operation to be carried out with six 15-man teams every day. The mission safety function was considered to be a less demanding task and hence was planned as a 12 hour shift with four days off. This required four 3-man teams to be used every day. The optimum crew loading and related work-rest cycles remain as an area for future study. However based on the foregoing approach, 32 additional crew members were estimated to be needed for this multi-shift coverage requirement. This increases the 4-Bay End Builder crew estimate to 417 people.

GEO CONSTRUCTION BASE CREW WORK SCHEDULE



NUMBER OF BASE PERSONNEL

Personnel requirements established by Boeing for operational SPS maintenance and flight transportation vehicles maintenance are added to the SPS construction crew established on the previous chart, giving a total personnel compliment of 827. The maximum number of personnel on one shift has been totaled at 358. There are times when the personnel on duty could be considerably less, i.e., during the construction crew's time off.

NUMBER OF BASE PERSONNEL

DISCIPLINE	PHASE I TOTAL	PHASE II TOTAL	MIDTERM ONE SHIFT
SPS CONSTRUCTION	(385)	(417)*	(199)
BASE MANAGEMENT	10	17	17
CONSTRUCTION	108	262	131
BASE SUPPORT & OPERATIONS	108	120	45
OPERATIONS SAFETY		18	6
SPS MAINTENANCE		(383)	(145)
REPAIR EQUIPMENT		260	130
MOBILE MAINTENANCE		83	NA
CREW SUPPORT		40	15
FLIGHT TRANSPORTATION MAINT		(27)	(14)
EOTV SUPPORT		8	4
OTV SERVICING		19	10
TOTALS		827	358

*ADDITIONAL PERSONNEL TO SUPPORT SHIFT ARRANGEMENT

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BASE/SATELLITE CONSTRUCTION ATTITUDE REQUIREMENTS

Only two of the nine requirements opposite appear to be significant when selecting the most desirable orbital attitude for the GEO Base. These are sun angle and EOTV unloading location. Both are discussed on subsequent charts.

The propulsion system penalty for attitude control in GEO is small and structural loading due to mass offset during construction appears lower than baseline design limits. Since maneuver capability is required for the base, SPS operational attitude and orbitkeeping do not affect construction attitude. Base stability for docking presents no problem since the GEO orbital rate is low. Location of communication antennas does not constrain attitude, as they can easily be located on the base open structure once other attitude requirements are imposed.

BASE SATELLITE CONSTRUCTION ATTITUDE REQUIREMENTS

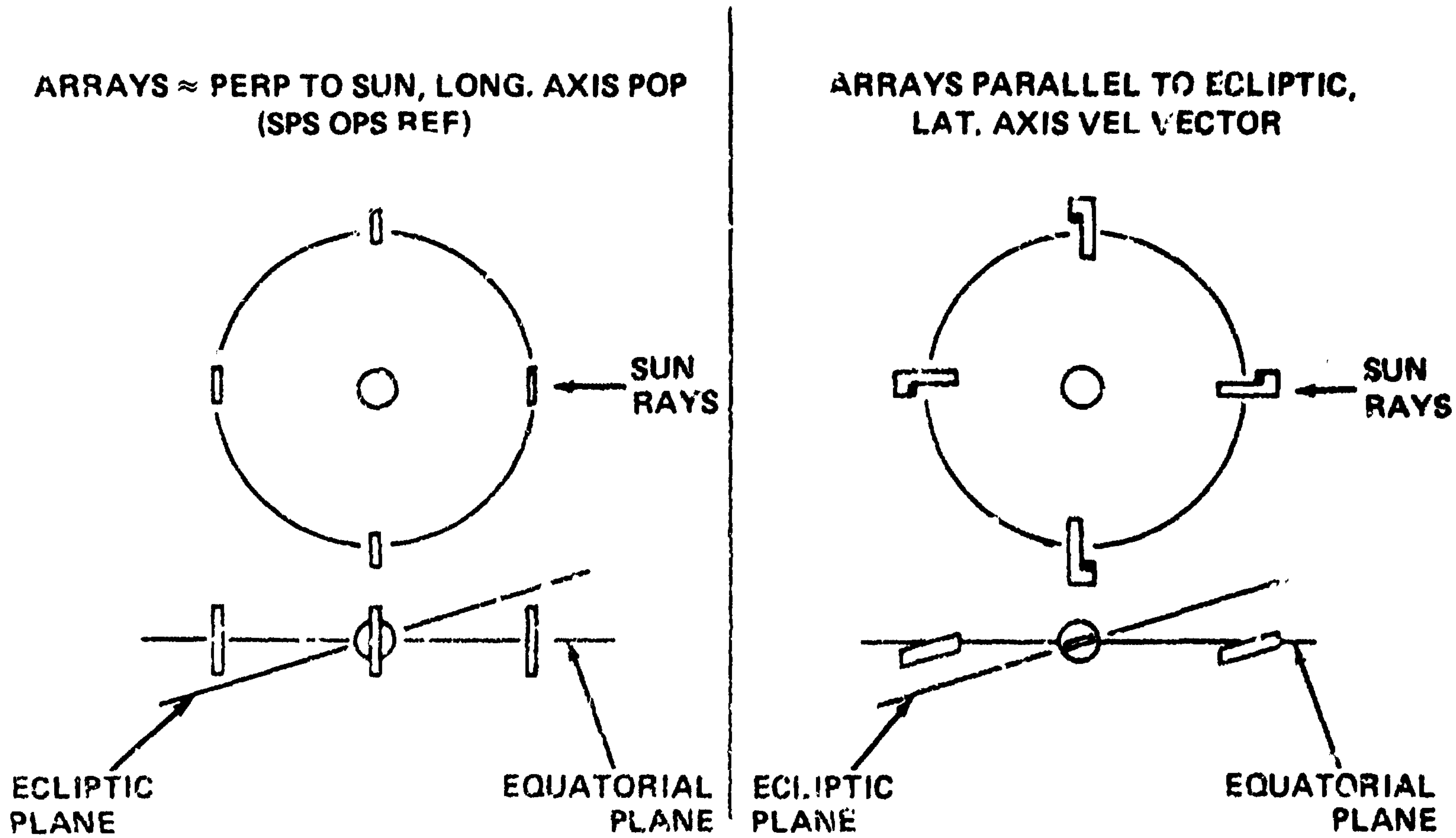
- BASE ATTITUDE CONTROL (GRAVITY & SOLAR PRESS TORQUE)
- √ SUN ANGLE
  - CONSTRUCTION LIGHTING
  - SPS SOLAR ARRAY DEPLOYMENT
  - BASE SOLAR ARRAY
- SPS OPERATIONAL ATTITUDE
- BASE MANEUVERS TO NEXT CONSTRUCTION SITE
- BASE STABILITY FOR DOCKING
- √ EOTV UNLOADING LOCATION
- COMMUNICATION ANTENNA LOCATION
- STRUCTURAL LOADING
- ORBITKEEPING

CANDIDATE GEO BASE SPS CONSTRUCTION ATTITUDES

If the SPS solar arrays are deployed in sunlight, high voltage is generated as the solar arrays are exposed to sunlight. Shorting cables could be used to terminate the solar array output, however, the method of handling these and the safety issues involved require study. Another approach to solving the problem is to orient the active side of the solar array from the sun. This issue also affects maintenance on an operational SPS.

Two basis attitude selections were evaluated: the SPS solar arrays positioned perpendicular to the sun and the solar arrays parallel to the sun's rays. Both attitudes minimize light impingement on the solar arrays during deployment, the first by inertially holding the active side of the arrays away from the sun and the second by maintaining the SPS edge on to the sun while the longitudinal axis points to earth. Other variations of the two attitudes shown opposite did not appear to offer any advantage.

CANDIDATE GEO BASE SPS CONSTRUCTION ATTITUDES



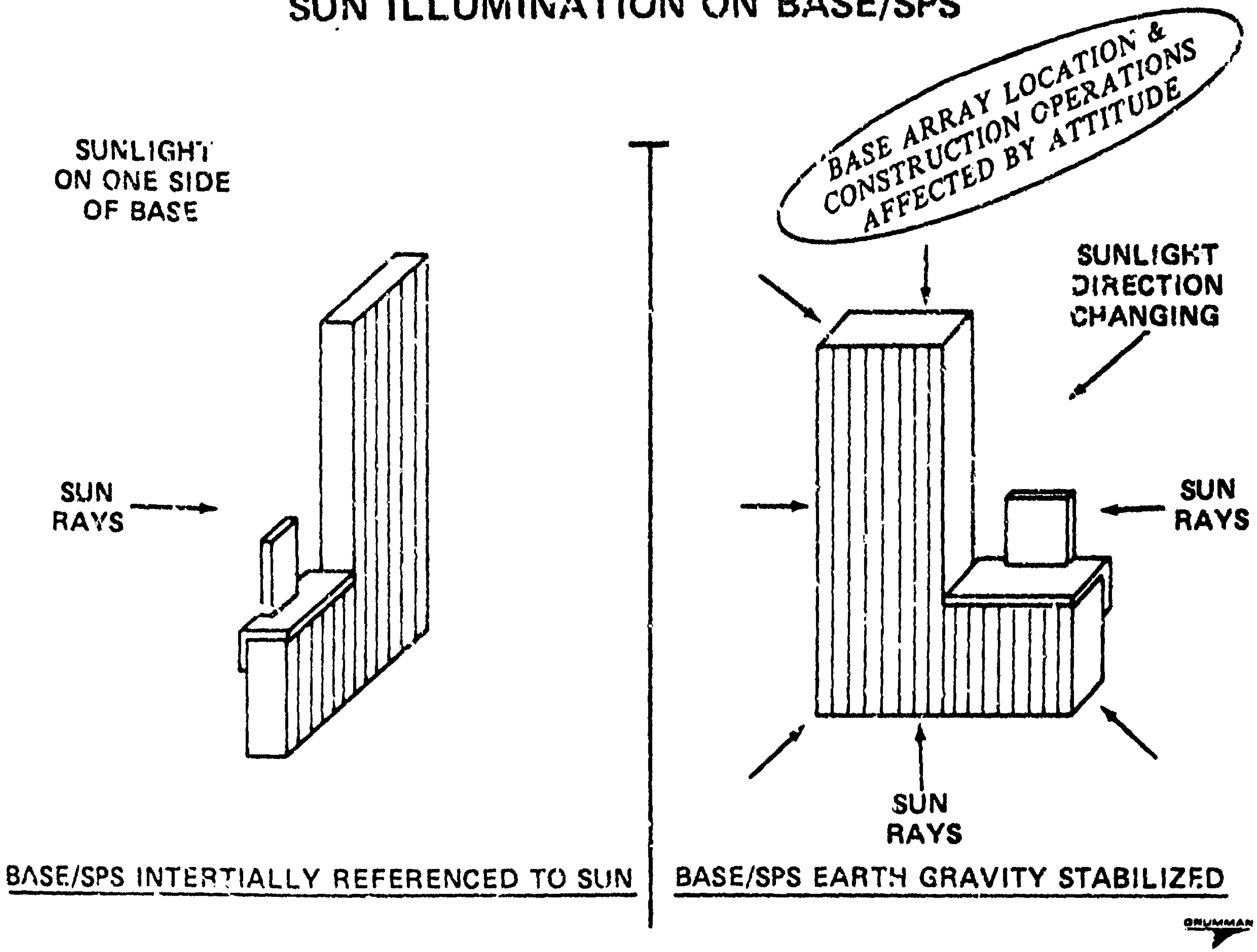
SUN ILLUMINATION ON BASE/SPS

The direction of sun illumination affects crew visibility during daily operations and placement of solar arrays on the Base.

The crew should not face the sun during construction or docking operations. Over-the-shoulder illumination is best. Construction operations require 3.6 MW of electrical power. Fixed solar arrays are less complicated than gimbal type.

The left-hand illustration opposite shows the Base/SPS inertially reference to sun, simplifying the selected location of fixed solar arrays, docking approach and construction illumination constraints. The right-hand illustration shows a more complex illumination situation as the sunlight direction varies on the gravity-reference Base/SPS. These factors are pertinent to the selection of the GEO Base construction attitude.

SUN ILLUMINATION ON BASE/SPS



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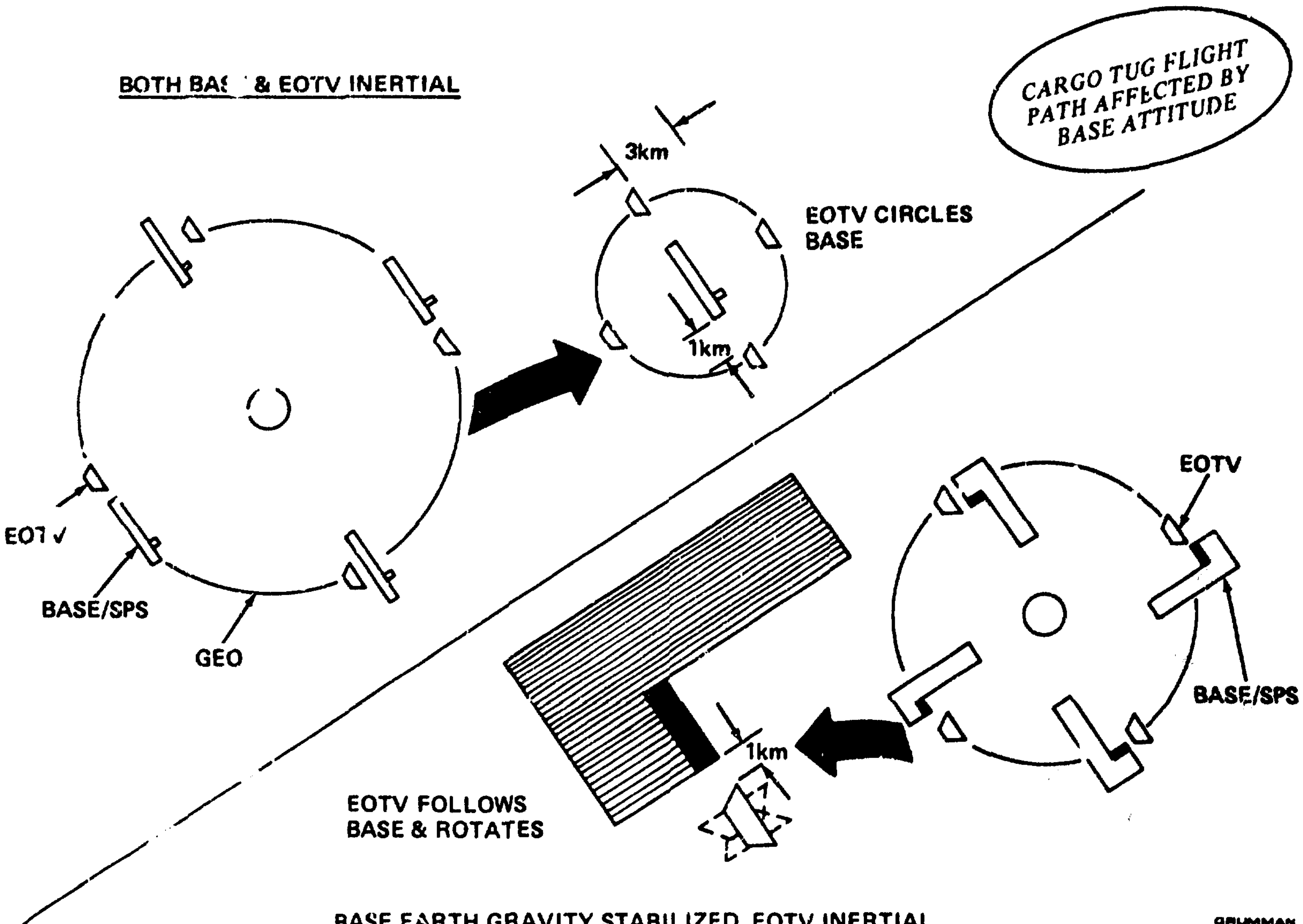
EOTV CARGO UNLOADING CONSIDERATIONS

The EOTV location as it stationkeeps with the Base affects the flight path of Cargo Tugs (CT) as they unload the EOTV, the distance the CTs must travel to docking ports, and EOTV stationkeeping propulsion requirements. If the EOTV is not in the same orbital path as the GCB then propulsion requirements are increased. Ideally, the EOTV should be located alongside of the dock ports at minimum distance consistent with safety requirements. Attitude requirements of the Base and EOTV and orbital mechanics may dictate a changing relationship between these two vehicles in GEO orbit and separation distances greater than 1 km (baseline).

The baseline operational attitude for the SPS is a candidate for construction operations. The illustration opposite shows this attitude with the EOTV stationkeeping during a 24 hour period. Both spacecraft are in the same orbital path with their solar arrays perpendicular to the sun. Note that the change in relative attitudes of the two vehicles during an orbit makes it appear that the EOTV is circling the Base/SPS. If this is the operating condition, then the two vehicles are separated by approximately 3 km at times and the CT flight paths are continually changing – an obvious impact on CT propulsion and control requirements. One solution is to maneuver between the two vehicles only when they are in the most favorable geometric location.

If the Base is earth gravity stabilized as shown, then the relative location of the Base and the EOTV remains fixed. The EOTV, however, rotates 360° every 24 hours with respect to the Base.

EOTV CARGO UNLOADING CONSIDERATIONS



BASE EARTH GRAVITY STABILIZED, EOTV INERTIAL

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QUALITATIVE COMPARISON OF CONSTRUCTION ATTITUDES

Both of the selected construction attitudes minimize illumination on the solar arrays, so other requirements shown in the table opposite were evaluated for attitude recommendation. The attitude that maintains the solar arrays perpendicular to the sun was selected. This permits the Base power arrays to be fixed on the structure, thus eliminating the need for rotary joints. This also allows construction operations to be planned, since the sun direction will always be the same. This attitude makes cargo tug operations more complicated, however, as the EOTV circles the Base and separation distance at times could be 3 km. One solution would be to limit cargo tug flights to those times when the EOTV is in a favorable position.

The second attitude evaluated, SPS arrays parallel to ecliptic, is worse for sun angle, but appears better for cargo tug flight. It remains in a fixed location with respect to the Base although it pivots around its own axis at orbital rate.

QUALITATIVE COMPARISON OF CONSTRUCTION ATTITUDES

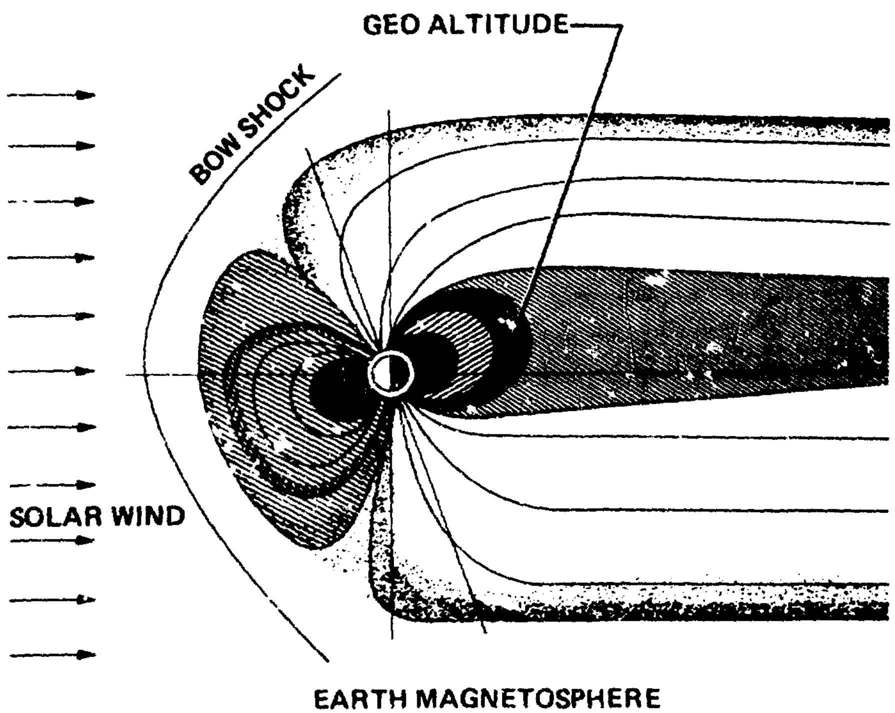
SIGNIFICANT REQUIREMENTS	√ SPS ARRAYS ≈ PERP TO SUN (INERTIALLY FIXED)	SPS ARRAYS PARALLEL TO ECLIPTIC (GRAVITY REF)
SUN ANGLE	• PERMITS FIXED BASE ARRAYS • SAME SUN DIRECTION FOR CONSTRUCTION OPERATIONS & DOCKING	• ATTITUDE MORE CRITICAL TO KEEP SUN OFF ARRAYS
EOTV UNLOADING	• MAY RESTRICT THE FLIGHT TO SPECIFIC TIME OF DAY	• EOTV POSITION FIXED WITH RESPECT TO BASE, ALTHOUGH EOTV ROTATES

SPS GEO RADIATION SOURCES

This illustration shows the magnetosphere and the radiation sources to which SPS systems and the assembly and maintenance crew will be subjected.

- The major sources of radiation at GEO orbit are the geomagnetically trapped electrons and protons, galactic cosmic rays and solar flare event particles.
- The trapped radiation particles undergo large temporal fluctuations (diurnal and during magnetic storm activity).
- Types of ionizing radiation important to SPS operations:
  - Electrons and secondary radiation: bremsstrahlung (with variation of factor of two due to parking longitude location)
  - Protons (flux from solar flare protons dominates) and secondary radiation protons, neutrons
  - Heavy ions (HZE), secondary radiation: protons, neutrons and lighter nuclei.
- Other sources
  - Onboard nuclear powered payloads and equipment
  - X-Ray equipment
  - Possible nuclear weapon detonations.

SPS GEO RADIATION SOURCES



- TRAPPED ELECTRONS & PROTONS
- GALACTIC COSMIC PARTICLES
- SOLAR FLARES
- OTHER SOURCES

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RADIATION EXPOSURE LIMITS & CONSTRAINTS (REMS)

This chart lists the current astronaut radiation exposure limits as defined by the National Academy of Science/Radiobiological Advisory Panel/Committee on Space Medicine in 1970. These astronaut radiation exposure limits are based upon a 5-year career and are presently included in the STS Payload Safety Guidelines Handbook. These limits are, of course, intended to cover all forms of ionizing radiation (natural and induced). Comparable radiation exposure limits are also shown for industrial workers, as defined by the Department of Labor OSHA regulations. The low OSHA limits are also contrasted with the maximum radiation limit allowed for each Apollo mission.

It is interesting to note that the average skin dose experienced by the Apollo astronauts was very low (about 1 rem), since no solar event occurred. Nevertheless the maximum limit for Apollo was established for a program of national importance that included less than one hundred volunteer astronauts. The OSHA standards, of course, apply to millions of industrial workers. The SPS construction base is presently estimated to have approximately 800 workers on board, which equates to a 10,000 man work force over a 30-year period. Hence, allowable SPS radiation limits may have to be established with respect to societal considerations.

RADIATION EXPOSURE LIMITS & CONSTRAINTS (REMS)

SHOULD INDUSTRIAL LIMITS APPLY TO SPS GEO SPACE WORK FORCE?

	ASTRONAUT*			INDUSTRIAL WORKER**	APOLLO MAX LIMIT
	SKIN (0.1mm)	EYES (3mm)	BONE MARROW (5cm)	BFO & EYES	BFO & SKIN
1 YR AVG DAILY RATE	.6	.3	.2		
30-DAY MAXIMUM	75	37	25		65 & 520*** PER MISSION
QUARTERLY MAXIMUM	105	52	35	3	
YEARLY MAXIMUM	225	112	75	5	
CAREER	1200 (5 yr)	600	400	235 (@ 65)	

* SPACE TRANSPORTATION SYSTEM PAYLOAD SAFETY GUIDELINES HDBK NASA/JSC - JSC 11123, JULY 1976

** FEDERAL REGULATIONS - LABOR PART 1910 OSHA - 1 JULY 1978

***APOLLO MISSIONS 7 TO 17 ONLY HAD ~ 1 REM AVG SKIN CREW DOSE-SINCE NO MAJOR SOLAR PARTICLE EVENTS OCCURRED

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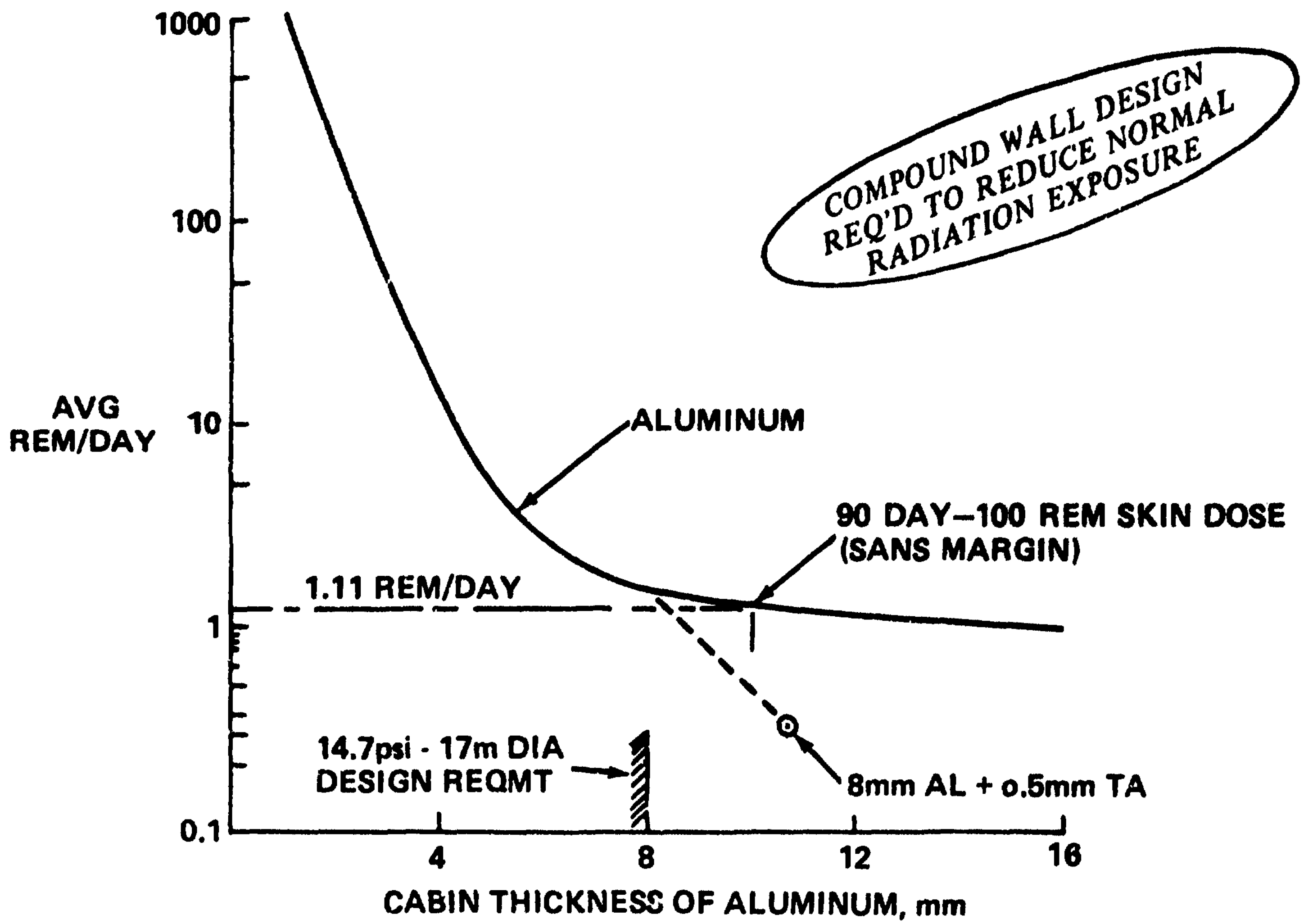
SHIELDING THICKNESS FOR GEO TRAPPED ELECTRONS PLUS BREMSSTRAHLUNG

The average REMs that a crew member will experience each day in geosynchronous orbit is plotted as a function of equivalent aluminum cabin wall thickness, as shown on the facing page. In order to reduce the skin dose to 1.11 REMs per day for the maximum quarterly exposure limit (i.e., 105 REMs less 5 REMs for OTV LEO/GEO transit) at least 10 mm of aluminum should be provided. Aluminum is not a very effective shield for this level of radiation due to Bremsstrahlung secondary radiation effects. However, by adding a thin inner layer of tantalum, the cabin radiation level can be lowered to provide a margin for other unscheduled radiation conditions (e.g., x-ray inspection, etc.). The use of compound wall design techniques is an effective way of coping with Bremsstrahlung which provides increased radiation protection for minimum shield thickness and weight. Practical shielding designs that can reduce the daily dose rate to OSHA levels require further study and remain as a technology issue.

SHIELDING THICKNESS FOR GEO TRAPPED ELECTRONS PLUS BREMSSTRAHLUNG (270° EAST LONGITUDE)



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SOLAR FLARE RADIATION PROTECTION REQUIREMENTS

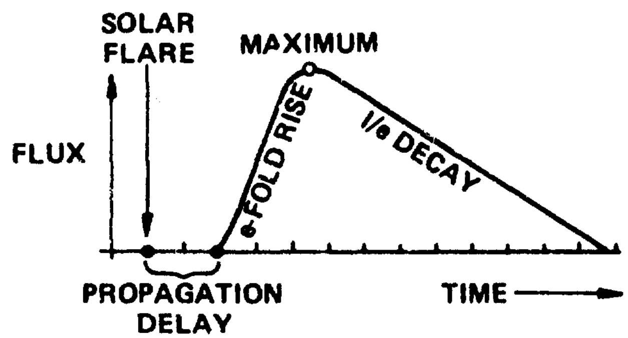
The GEO base solar flare radiation protection system must be able to provide timely warning of a high energy solar event, so that the crew can safely reach a radiation shelter to ride out the storm. The characteristics of a typical solar event are shown on the facing page, together with related data on the severity and duration of prior solar events. Minimum aluminum shielding thickness requirements are provided.

Once a solar flare is observed, a 20 to 30 minute delay occurs in particle propagation before an increase in the background energy level is detected. From the onset of increased radiation, the maximum flux level may be attained within 15 minutes to a few hours. The peak intensity, in turn, may last only intermittently or for a few hours and the subsequent decay period may be over in a matter of hours or days. Data from the 20th solar cycle shows that the highest energy event recorded lasted for five days and that a few lower energy events lasted 10 days. Hence, the radiation storm shelter must be able to support the crew life support functions for several days.

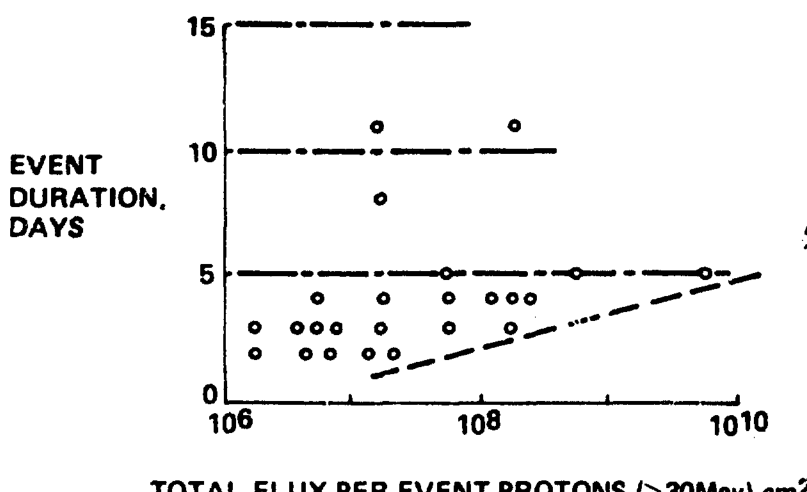
In the upper right part of the chart, the frequency of solar events is plotted as a function of the severity of the event (protons/cm^2). Smoothed historical data are shown for the two most recent solar cycles. Cycle 21 is now underway and resembles cycle 19 rather than cycle 20. The lower righthand part of the figure shows the cabin wall thickness necessary to protect against this range of event sizes. A typical cabin wall thickness needed for shielding trapped electrons in GEO is also shown at about 4 gm/cm^2 (i.e. 1.2 cm of aluminum). A 4 gm/cm^2 shield gives protection for any event up to 1×10^9 p/cm^2 flux, however, a minimum thickness of 10 gm/cm^2 is needed for a major solar event (Aug 1972) provided the crew is also equipped with personal shielding for the eyes and testes during peak exposure. Development of a real time solar flare alert system with flux forecast is needed. If the alert system can be triggered at predetermined energy levels below the nominal wall radiation protection level, then a built-in margin for error in forecasting accuracy could be achieved.

SOLAR FLARE RADIATION PROTECTION REQUIREMENTS

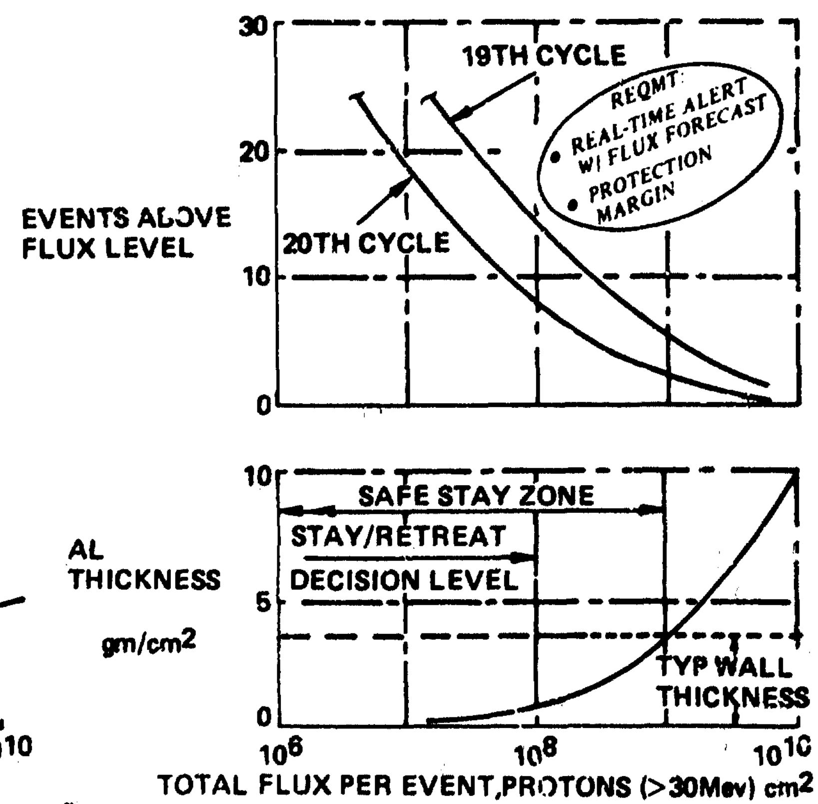
SOLAR EVENT CHARACTERISTICS



20TH CYCLE SOLAR EVENT DATA



SOLAR EVENT FREQUENCY & MIN SHIELDING THICKNESS



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SPS GEO BASE RADIATION DESIGN CONSIDERATIONS

The allowable crew dose for the SPS GEO construction base remains to be established. Total accumulated dose limits are required for the entire mission profile, that is, time in LEO, LEO/GEO transit and the GEO base. How much margin should be provided for unscheduled exposure and whether the astronaut allowed radiation levels are applicable to SPS are areas for further study.

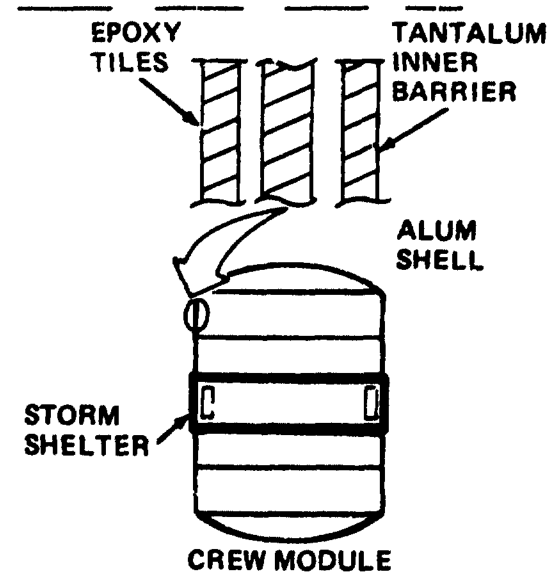
Protection against trapped electron flux in geosynchronous orbit must be factored in all aspects of GEO base operations and design, which include IVA assignments in remote work stations, free fliers, crew bases and crew habitation modules. We propose a multilayered cabin wall of 4 gm/cm^2 aluminum equivalent for the crew module as shown in the figure. The other IVA crew stations could be designed with lighter shielding provided that the total allowable dose is not exceeded. In addition, if EVA operations are needed they should be conducted near local midnight to minimize normal belt radiation exposure. However, EVA should be avoided during large scale fluctuations due to geomagnetic disturbances. The present SPS suit must be upgraded to provide added protection for GEO EVA (i.e., between 1.5 and 4 mm equivalent aluminum.)

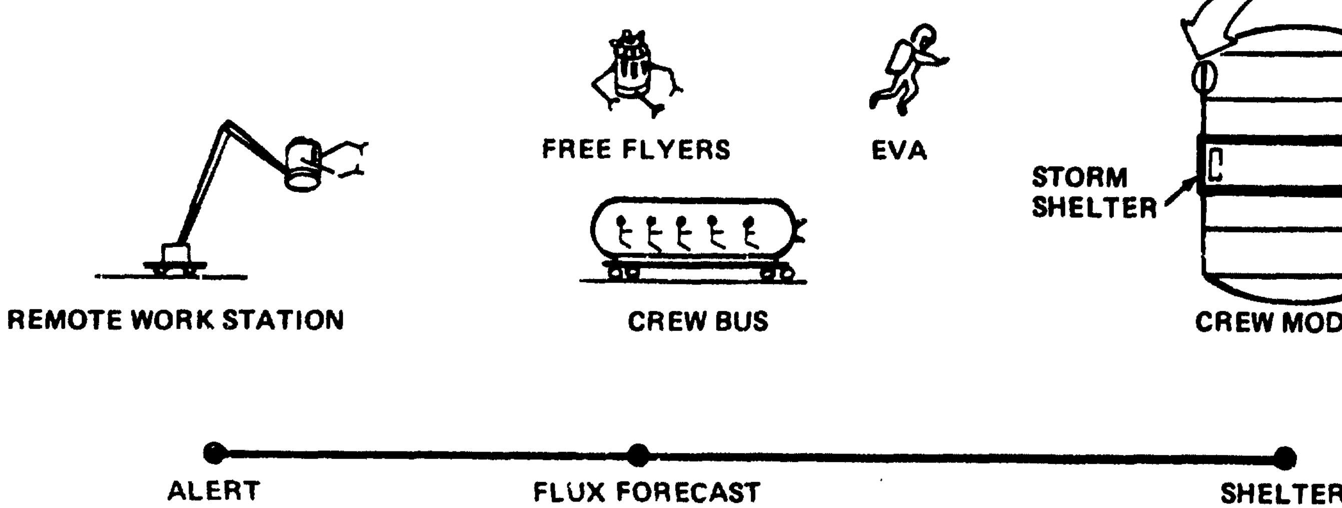
Protection against solar flares requires an adequate flare alert warning system that will allow all GEO base workers on remote IVA or EVA assignments to retreat to the nearest storm shelter. Means for protecting stranded workers at these remote locations need to be considered together with the systems required to implement their rescue. The storm shelter is provided with 20 gm/cm^2 of multilayered aluminum equivalent thickness. Additional shielding benefits can be attained by placing internal equipment arrangements against the outer wall.

Protection against high energy heavy ions (HZE) requires further study. Although the dose from these HZE particles is small it is important because of possible biological effects.

SPS GEO BASE RADIATION DESIGN CONSIDERATIONS

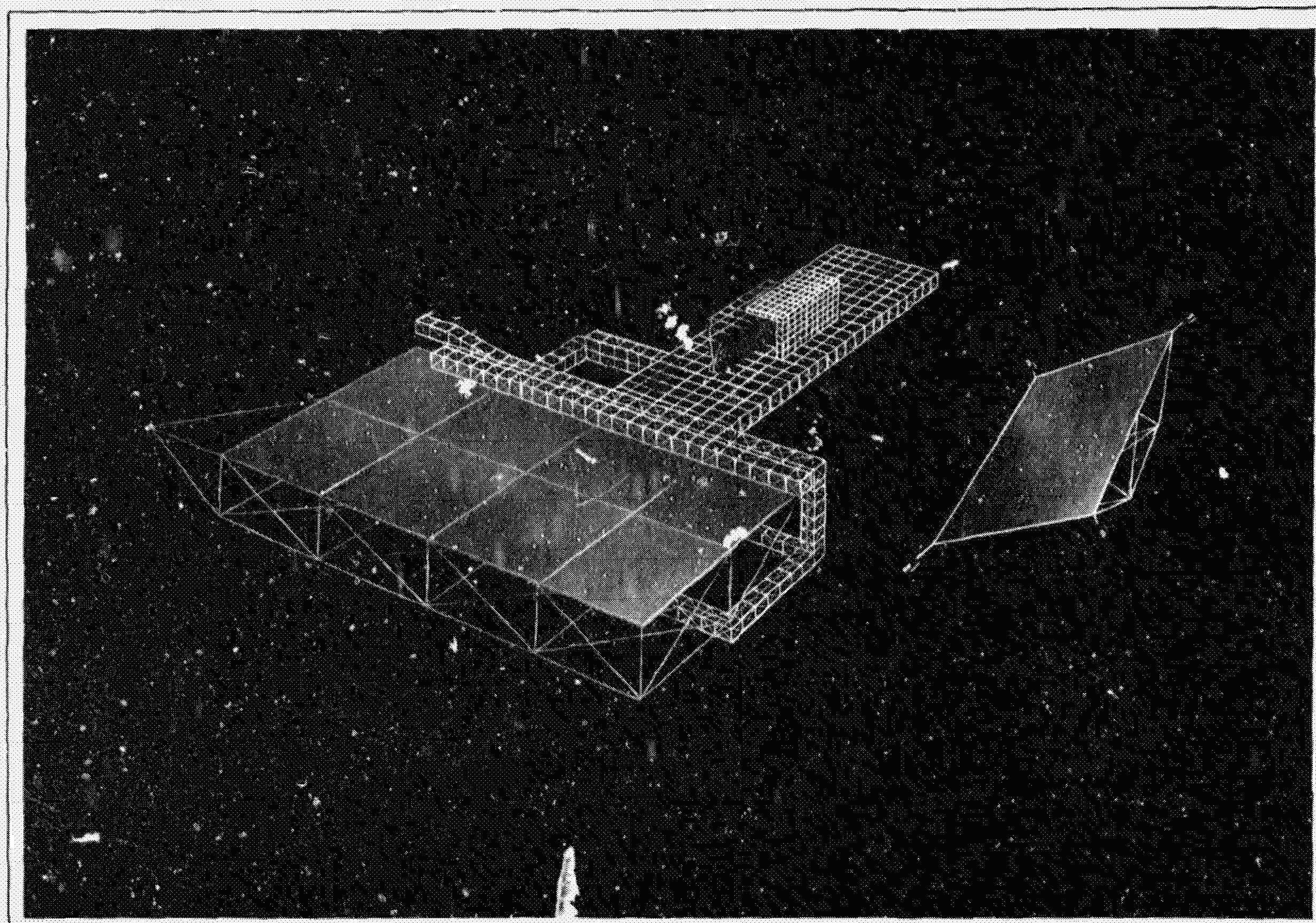
- ALLOWABLE CREW DOSE – 60% ASTRONAUT LEVEL?
- PROTECTION AGAINST TRAPPED ELECTRON FLUX –MULTI-LAYERED CABIN WALL (4g/cm2 AL EQUIV)
- PROTECTION AGAINST SOLAR FLARES





- HZE BIOLOGICAL EFFECTS/PROTECTION?

SPS CONSTRUCTION FIRST PASS



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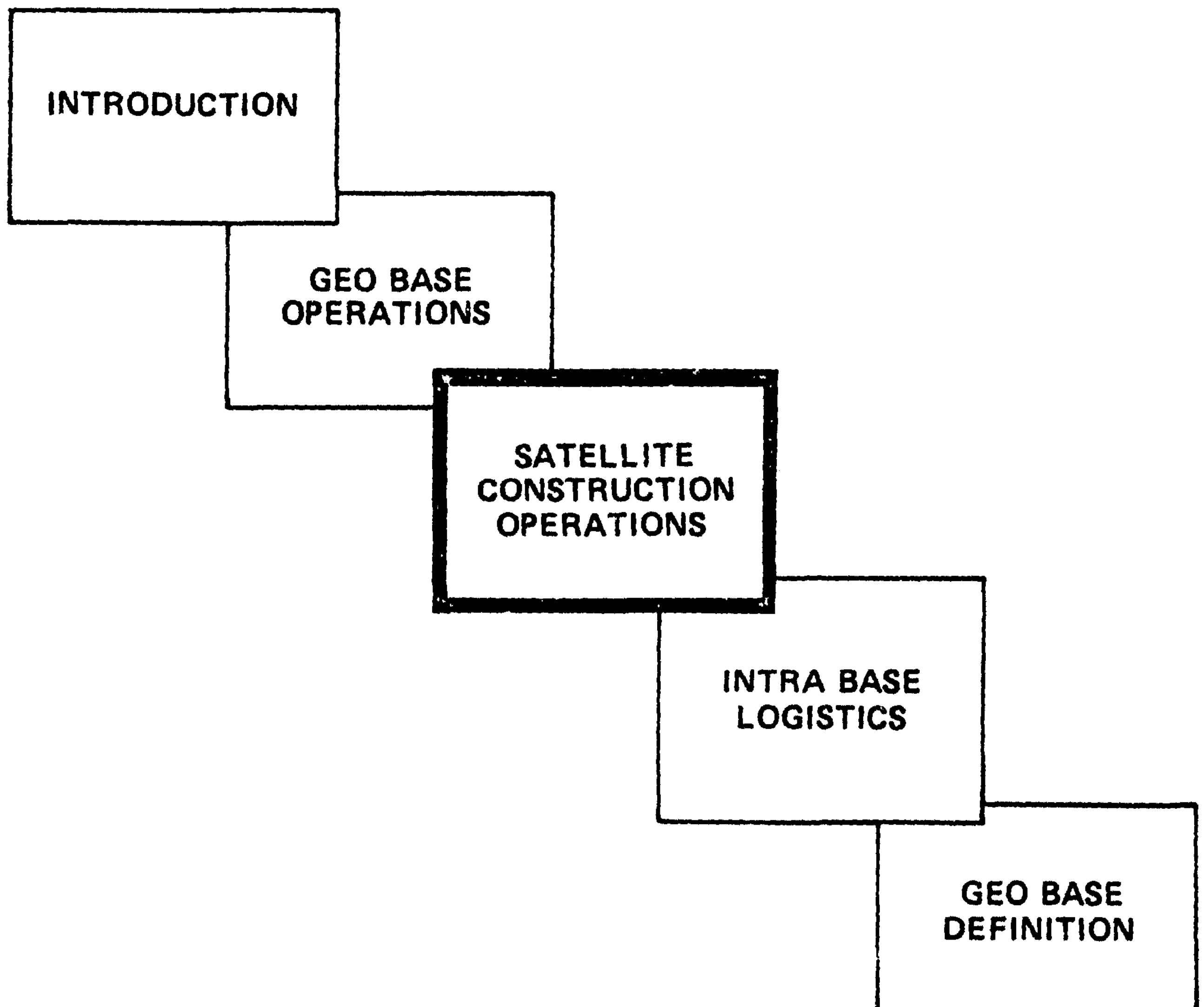
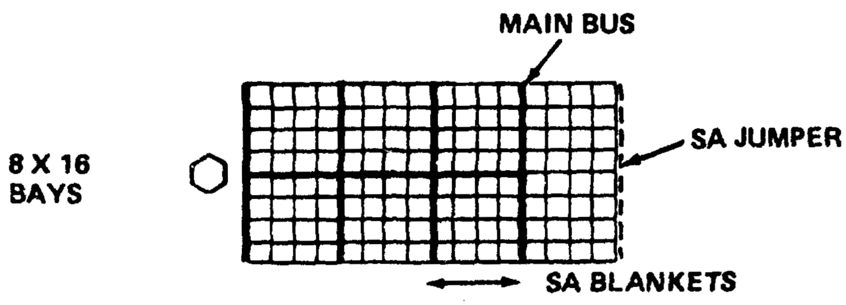

INTRODUCTION
GEO BASE OPERATIONS
SATELLITE CONSTRUCTION OPERATIONS
INTRA BASE LOGISTICS
GEO BASE DEFINITION

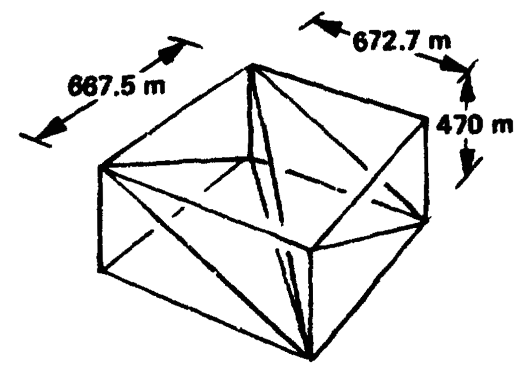
SPS PHASE 2 CONSTRUCTION REQUIREMENTS AND ISSUES

The 5000 MW reference solar power satellite is to be constructed entirely in GEO and is to be fully assembled in 6 months. The reference satellite has a single antenna located at one end of a large photovoltaic energy conversion system as shown on the facing page. The 8 x 16 bay energy conversion system features a hexahedral braced structure, longitudinal solar array blanket installation and multiple power buses. The satellite construction approach includes the 2 pass longitudinal buildup of the energy conversion system and the 16 row lateral buildup of the power transmission antenna as defined in Boeing's Phase I final report (Volume III, D180-25037-3) The GEO construction operation is to rely upon normal IVA assembly methods. A broad range of technology issues (many of which are beyond the scope of this study) must be addressed to cover all aspects of the SPS construction process. As the reference system matures, the satellite construction approach must be reexamined for the energy conversion, power transmission and interface systems. In addition the structural assembly methods should be well understood to the level of beam fabrication, handling and joining. Techniques for installing the major subsystems (i.e., solar arrays, buses and subarrays) must be further developed and the requirements for construction equipments need further refinement. In addition, the structural dynamic, thermodynamic and control interactions between the base and the satellite should be investigated and defined. Other areas to be examined include methods for berthing or mating of large system elements, techniques for in-process inspection and repair, and concepts for implementing satellite final test and checkout.

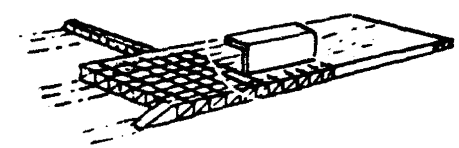
SPS PHASE 2 CONSTRUCTION REQUIREMENTS & ISSUES

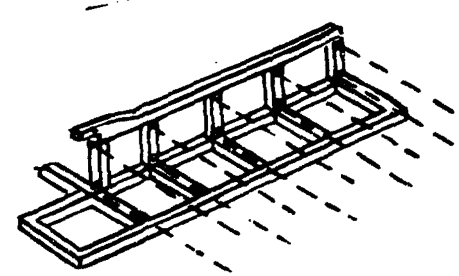
- ASSEMBLE BASELINE 5 GW SATELLITE IN 6 MONTHS





- 4 BAY END BUILDER (PH-1, REF S/S DESC D180-25037-3)
  - 2 PASS LONG. ENERGY CONV ASSY
  - 11 ROW LATERAL ANTENNA ASSY
- IVA ASSEMBLY METHODS - EVA EMERGENCY LIMITED
- SPS CONSTRUCTION ISSUES
  - SATELLITE CONSTRUCTION APPROACH
  - STRUCTURAL ASSEMBLY METHODS
  - SUBSYSTEM INSTALLATION TECHNIQUES
  - CONSTRUCTION EQUIPMENT REQM'TS
  - SATELLITE SUPPORT & BASE INTERACTIONS
  - HANDLING & MATING LARGE SYSTEM ELEMENTS
  - IN PROCESS INSPECTION & REPAIR
  - FINAL TEST & CHECKOUT





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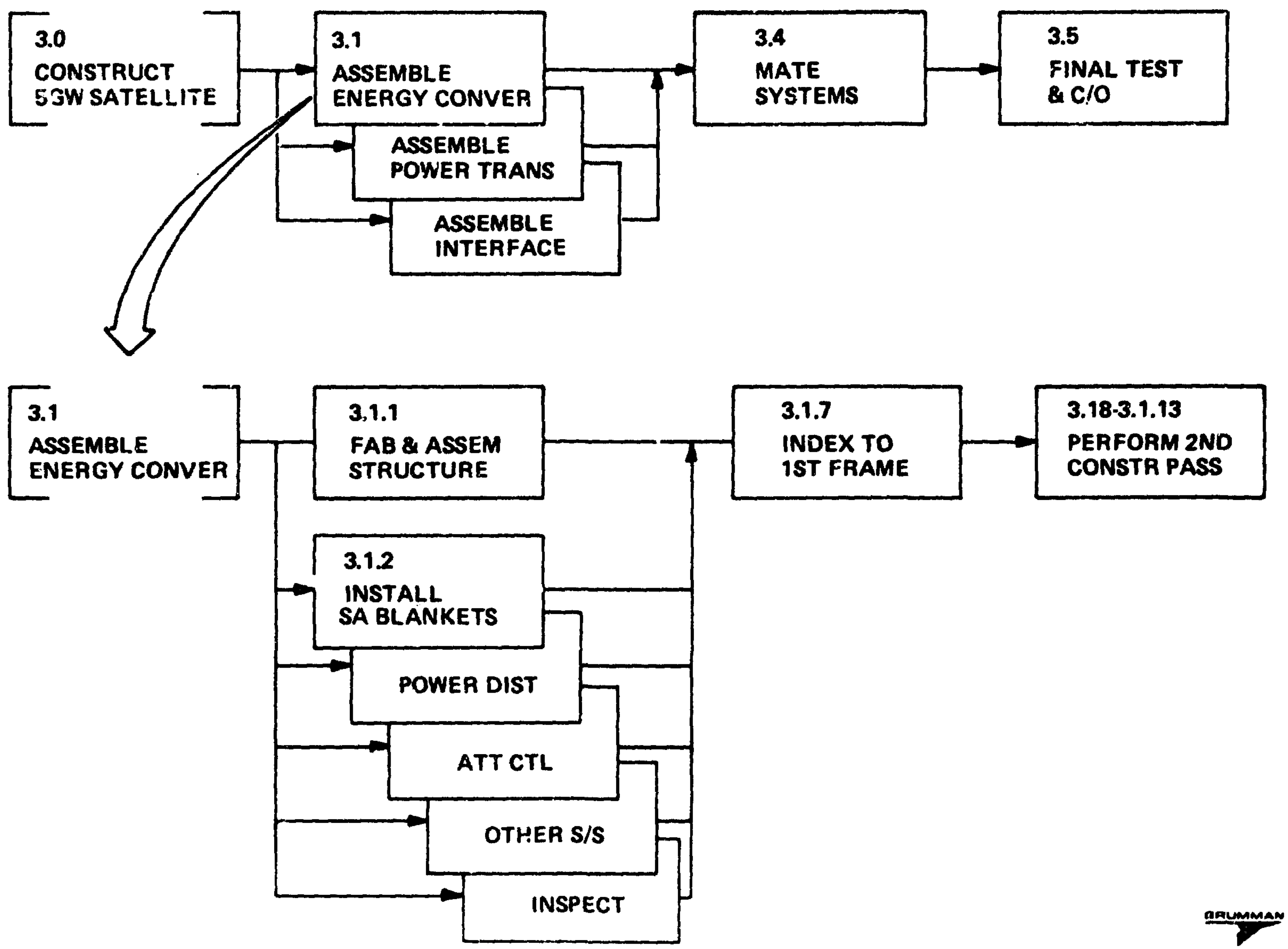
SATELLITE CONSTRUCTION OPERATIONS ANALYSIS

SPS construction operations are analyzed from the top down, by defining the required steps at each level of the construction sequence. As shown in the facing page, construction of the reference satellite systems includes parallel assembly of energy conversion, power transmission and interface elements. When these system elements are fully assembled, they will be mated and integrated to form the complete solar power satellite. The construction process ends with final test and checkout of SPS systems.

A further breakdown of the assembly operations for the energy conversion systems is shown by the abbreviated flow in the lower half of the chart. This assembly activity includes the fabrication and assembly of the structure for the first construction pass (3.1.1) and the parallel installation and inspection of required subsystems (e.g. solar array blankets, power distribution, etc.). When the first half of the satellite energy conversion system has been constructed, the base will be indexed back along the site of the satellite structure to a position adjacent to the first frame (3.1.7). The second construction pass begins from that point and includes the fabrication and assembly of the remaining structure together with the parallel installation of other subsystems.

SATELLITE CONSTRUCTION OPERATIONS ANALYSIS



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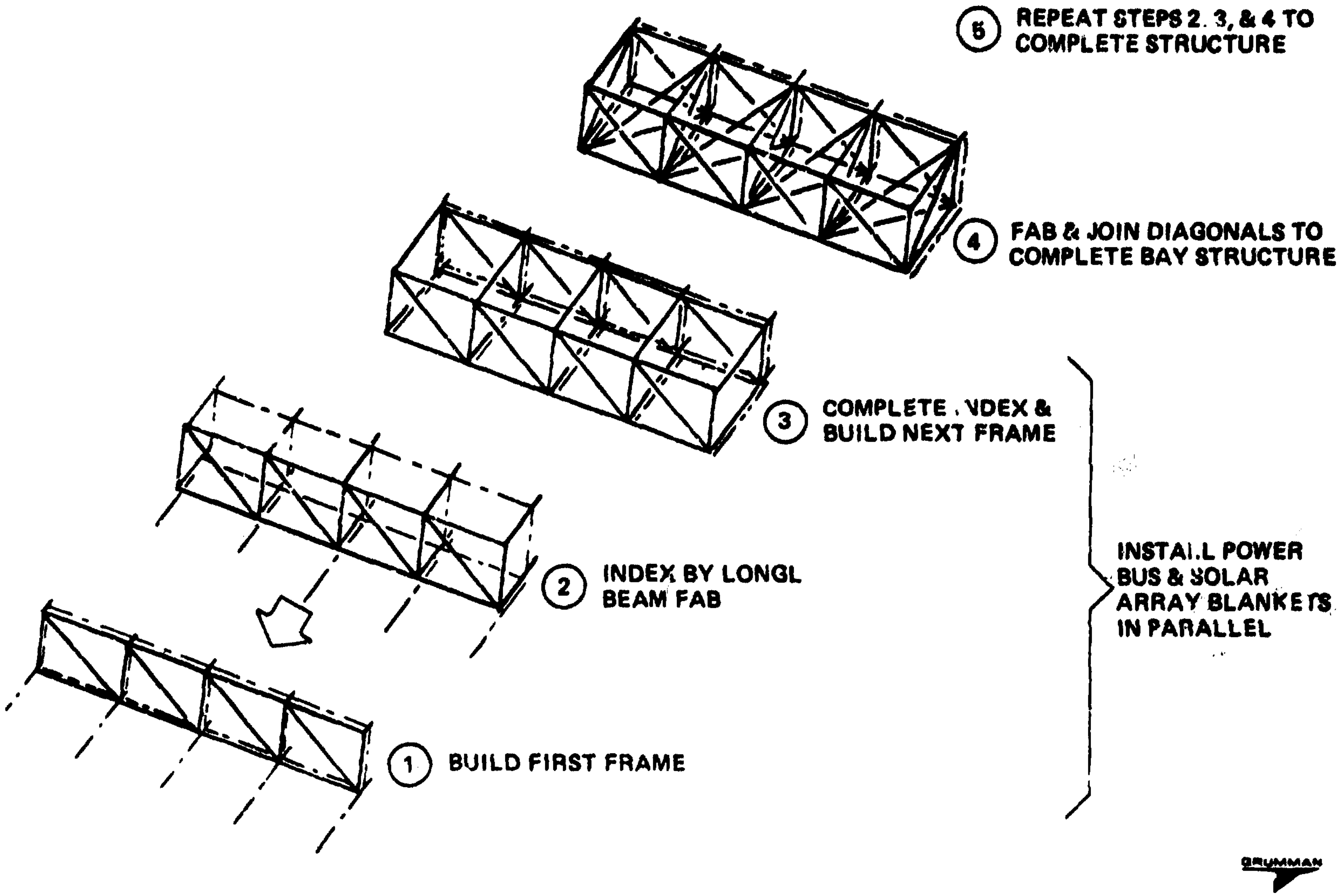
END BUILDER STRUCTURAL ASSEMBLY SEQUENCE

The end builder construction system is tailored to the structural cross section of the satellite and uses ten (10) dedicated semi-fixed beam machines to automatically favricate continuous longitudinal members. Lateral and diagonal members of the structural assembly are fabricated by three (3) mobile beam machines. The assembly sequence as illustrated begins with Step 1, the assembly of the first frame and its attachment to the longitudinal members. The structural members of the frame are fabricated by three mobile beam machines that travel from one position to the next. The upper lateral beam is fabricated and then positioned for assembly. As this member is being joined, the mobile beam machines fabricate the other members of the frame needed to complete the assembly. Step 2 indexes the frame for one bay length by fabricating the continuous longitudinal beams from the dedicated beam machines. In Step 3, the next frame is built as in Step 1. During these three steps, power busses and solar array blankets are installed in parallel. The solar array blankets are deployed in the direction of build, are attached to the upper lateral beams and are fed out of cannisters as the structure indexes. Longitudinal busses are installed "on the fly" as the structure is indexed; lateral busses are installed before a bay is indexed. In Step 4 the bay structure diagonal beams are fabricated and assembled to complete the bay. This bay is then indexed, as in Step 2, and the entire sequence repeated until the energy conversion structure is built.

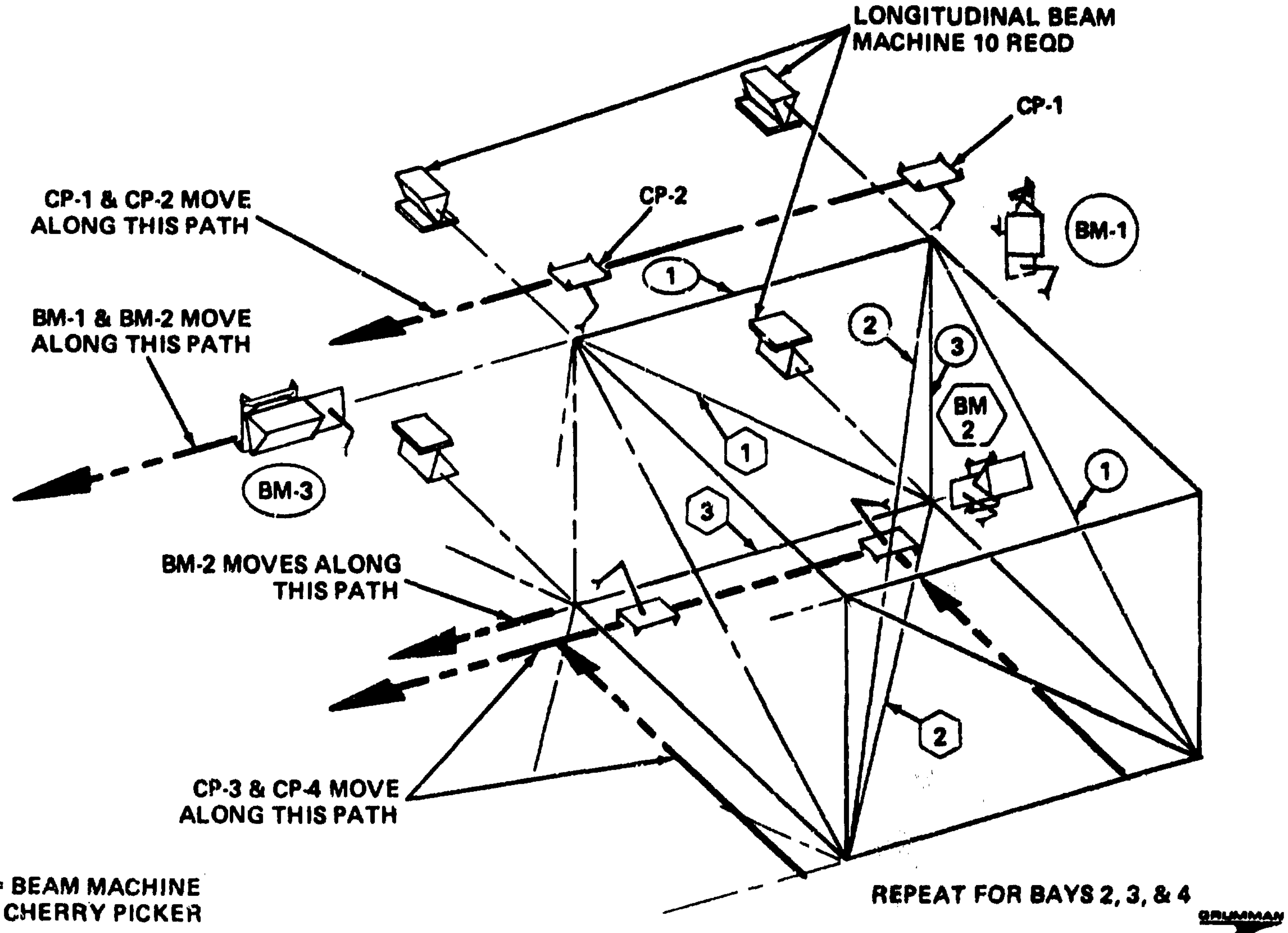
END BUILDER STRUCTURAL ASSEMBLY SEQUENCE



ENERGY CONVERSION STRUCTURE ASSEMBLY EQUIPMENT & SEQUENCE – 1ST BAY

This illustration identifies the assembly equipment and construction sequence required to assemble the structural bays of the energy conversion module. The first bay of the four-bay pass is shown requiring the use of longitudinal beam machines (semi-fixed), three (3) mobile beam machines and four (4) cherrypickers. The operating paths of the mobile beam machine and cherrypickers are also defined along with the fabricating sequence of each of the mobile beam machines. This sequence is then repeated for bays 2, 3 and 4.

ENERGY CONVERSION STRUCTURE - ASSEMBLY EQUIPMENT & SEQUENCE - 1ST BAY



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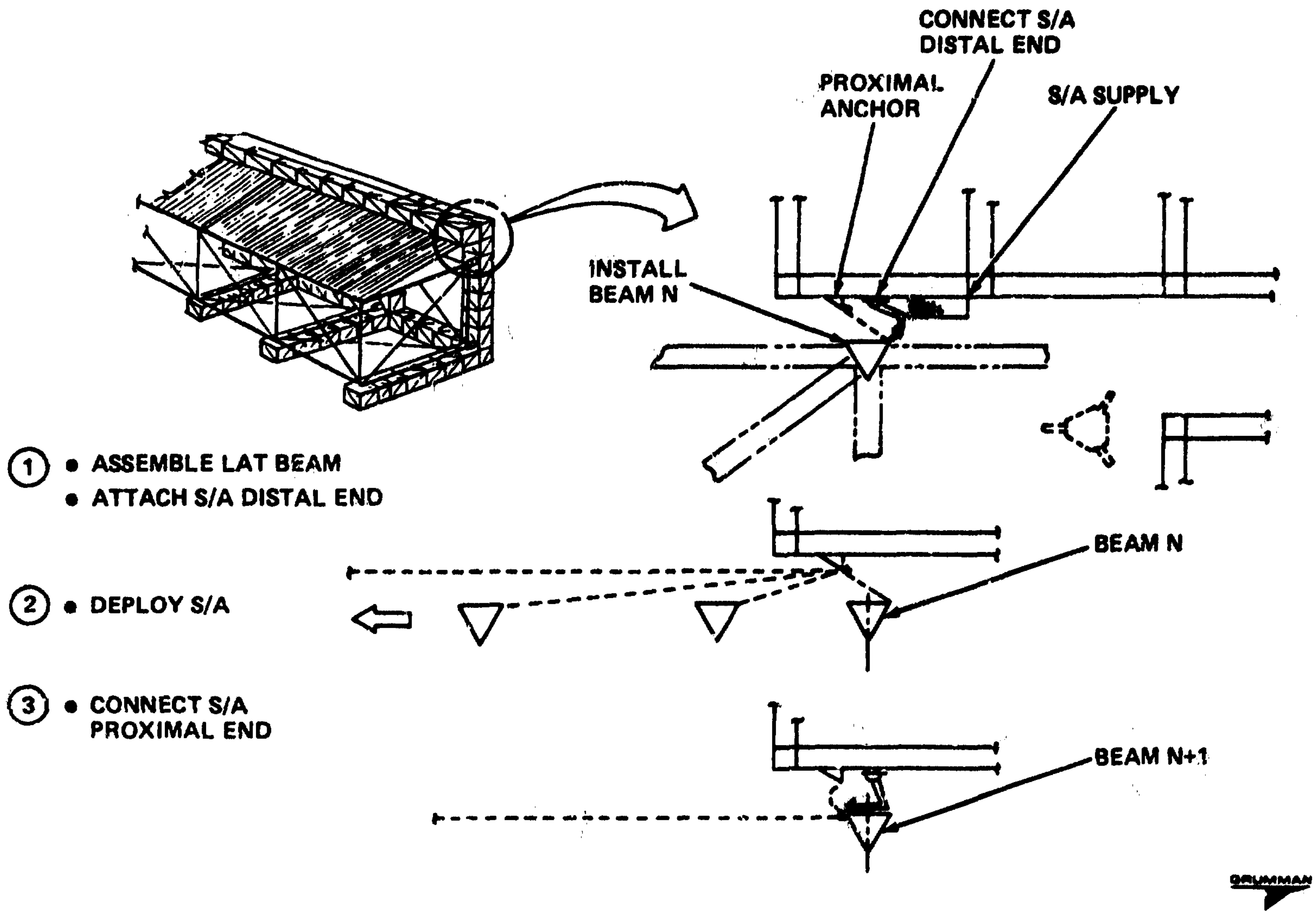
COUPLED FRAME ASSEMBLY/SOLAR ARRAY DEPLOYMENT

The installation of solar arrays occurs at the same work station in the base as the assembly of in-plane structural frame elements, to obtain maximum time-line benefits from parallel activities.

Subsequent to the installation of a 12.7 m solar array support beam, the cherry picker removes an SA box from the supply crib shown and fastens it to the proximal anchor. The distal-end of the blanket is then connected to the beam. When the frame has been indexed one bay away, the blankets are fully deployed and the box is removed from its anchor support fittings and fastened to the next 12.7 m support beam to complete the cycle.

COUPLED FRAME ASSEMBLY/SOLAR ARRAY DEPLOYMENT

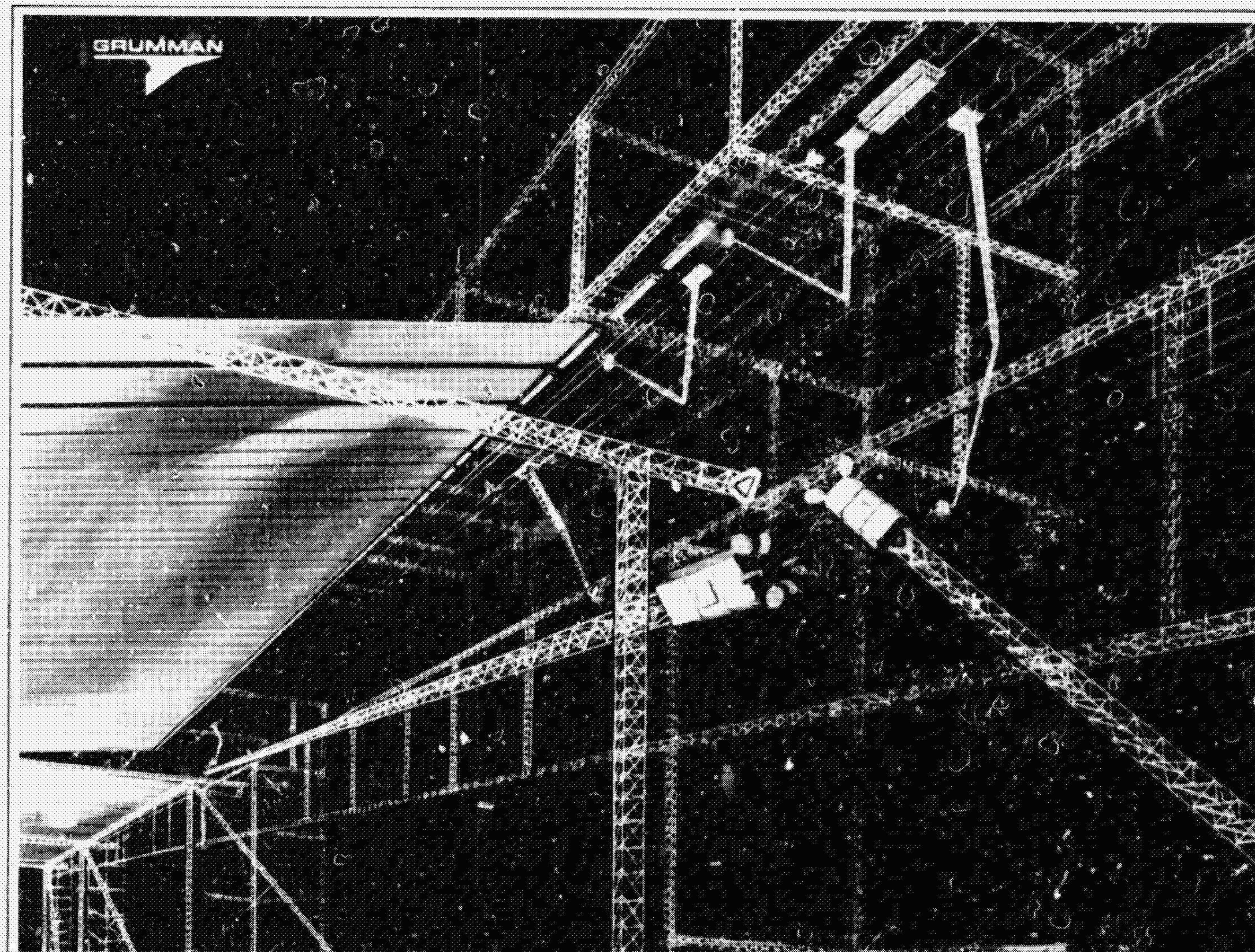


SPS ASSEMBLY OPERATIONS

The facing page rendering depicts the construction activities at levels F, G, and H of the energy conversion construction facility. These levels are utilized in the construction of the upper surface of the energy conversion module. Shown nestled in the facility structure is the 7.5 m longitudinal beam machine (semi-fixed), and operating from a horizontally mounted track system are two mobile beam machines. One beam machine is shown fabricating the 7.5 m bracing beam and the other the 12.7 m lateral (solar array support) beams. Located overhead on the facility overhang and operating from a track system, cherrypickers are used to maneuver and attach the completed beams. The complex operations of these two cherrypickers in the maneuvering, handing-off and installation of beam lengths of approximately 600 to 1000 meters requires further study.

Solar array blanket deployment and installation is coupled with the end builder structural assembly sequence. Shown are the blanket installers operating from a track system mounted on the facility overhang. The solar array blankets are deployed from canisters mounted on the overhang. Replacement canisters are shown being moved into place and installed at their deployment station by a mobile flatbed cherrypicker.

SPS ASSEMBLY OPERATIONS



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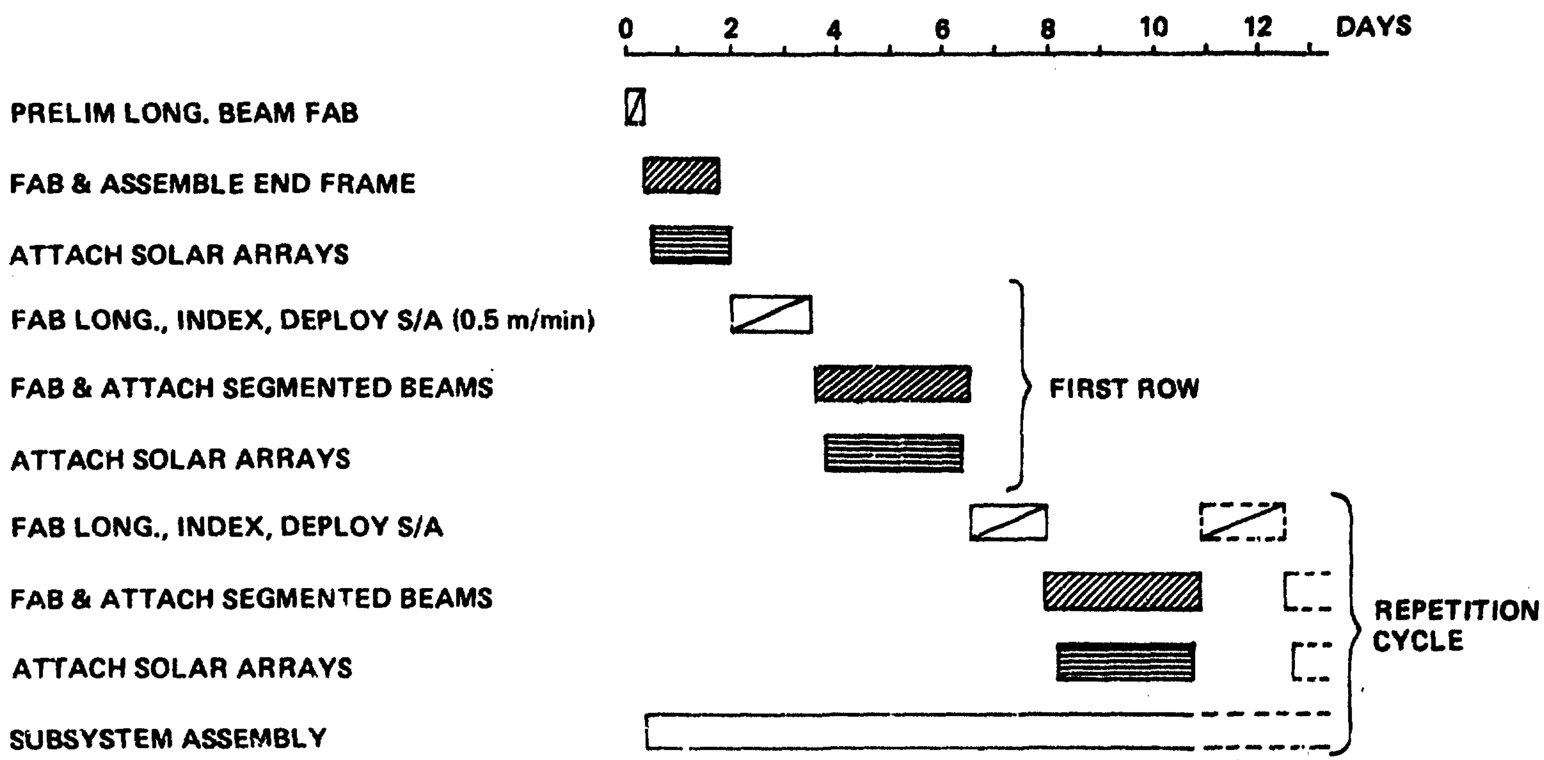
ENERGY CONVERSION SYSTEM ASSEMBLY OPERATIONS TIMELINE

The 4 Bay End Builder construction operations timeline has been updated to show the initial fabrication of longitudinal beams required to allow the assembly of the first end frame. The beam fabrication operations shown on the facing page have also been updated to include the installation of beam end fittings and related space frames on the continuous longitudinal beams. The impact of this update has only added two days to the original 180.5 day timeline.

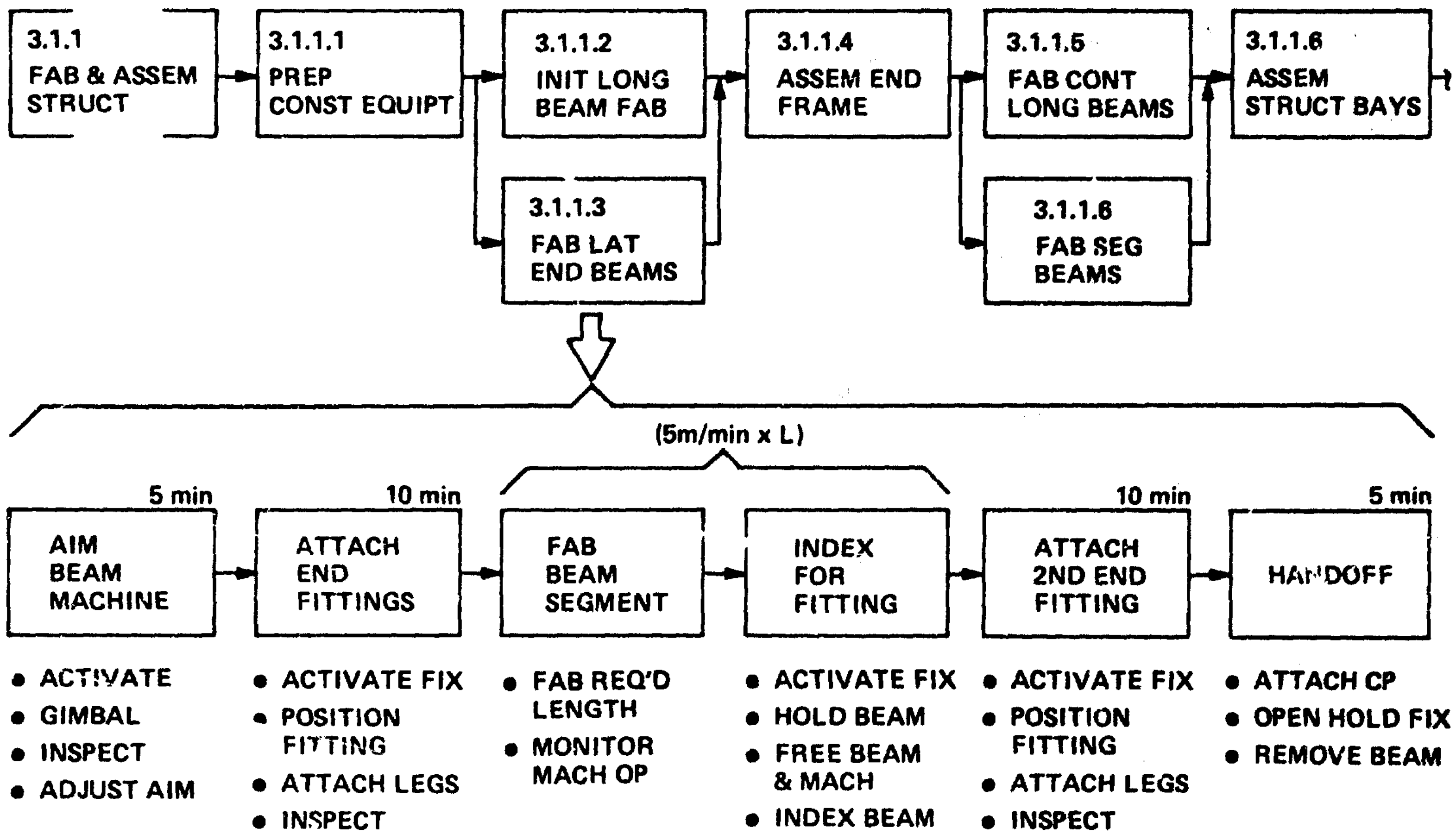
ENERGY CONVERSION SYSTEM ASSEMBLE OPERATIONS - TIMELINE



ENERGY CONVERSION STRUCTURE FABRICATION & ASSEMBLY FLOW

A further breakdown of the SPS structure fabrication and assembly operations is shown on the facing page. This functional flow defines the beam fabrication requirements leading to the assembly of the first 4 bay wide end frame for the energy conversion structure. It also defines the beam fabrication requirements which permit the assembly of structural bays (16 rows) for the first construction pass. The major functional blocks, such as 3.1.1.3-fabricate lateral end beams, are defined to the level of detail illustrated by the flow in the lower half of the chart. Times are estimated for each of the functions which comprise the fabrication of segmented lateral beam for subsequent attachment to the continuous longitudinal beams. The attachment of beam end fittings is defined for both ends of the beam as it emerges from an automatic beam machine. The need for an indexing beam holder is also identified as a prerequisite to the attachment of the second end fitting.

ENERGY CONVERSION STRUCTURE FABRICATION & ASSEMBLY FLOW



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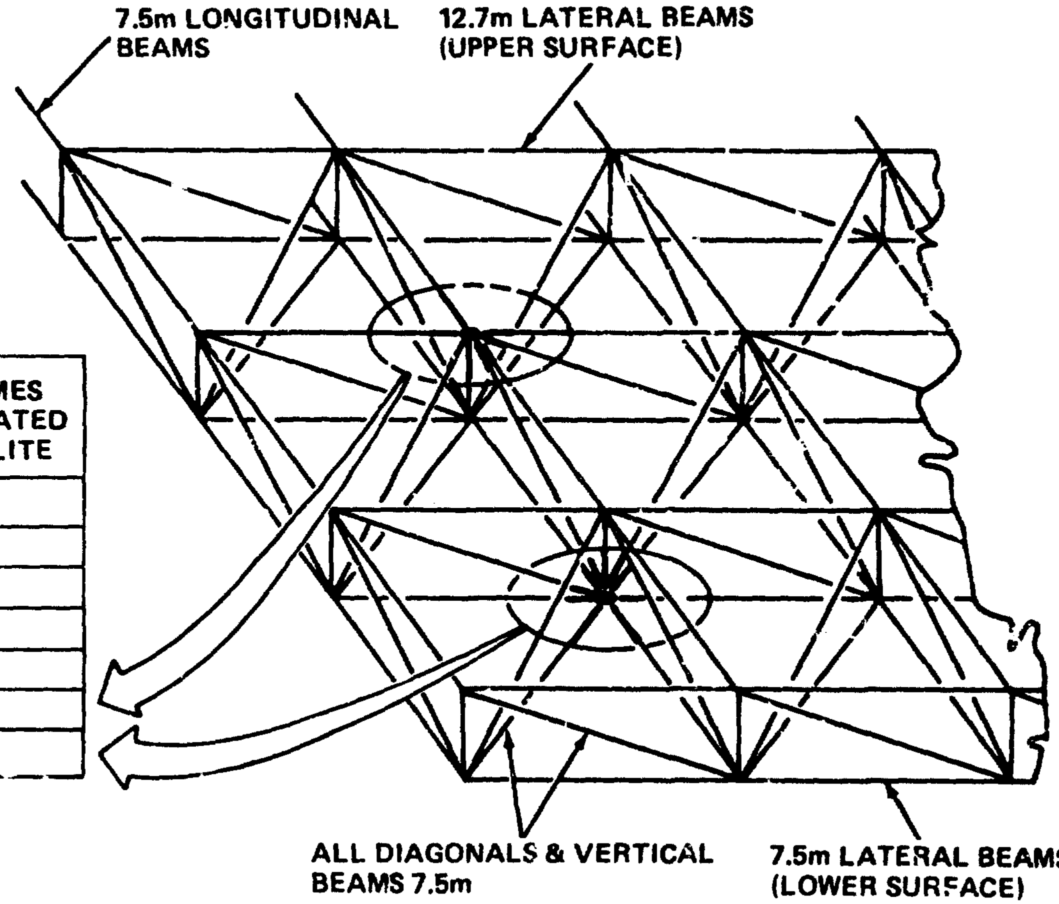
STRUCTURAL JOINT CONFIGURATION

The end builder system uses beam machines to automatically fabricate continuous longitudinal beams. Several types of structural joints (i.e., nodal fitting, butt fitting and space frame) can be adapted to the end builder construction system. To help in the selection of the joint fitting best suited for fabrication, the energy conversion structural arrangement was reviewed to identify the requirements and complexity of its structural joints.

The results of the review are shown on the opposite page. The structure arrangement consists of 305 major structural joints. The number of structural members intersecting at three joints varies from 3 to 10 members with the predominant repeatable joints being the 8 member intersection on the upper surface and a 10 member intersection on the lower surface.

STRUCTURAL JOINT CONFIGURATION

NO. OF MEMBERS AT JOINT	NO. OF TIMES JOINT REPEATED ON SATELLITE
3	2
4	1
5	11
6	37
7	37
8	112
10	105



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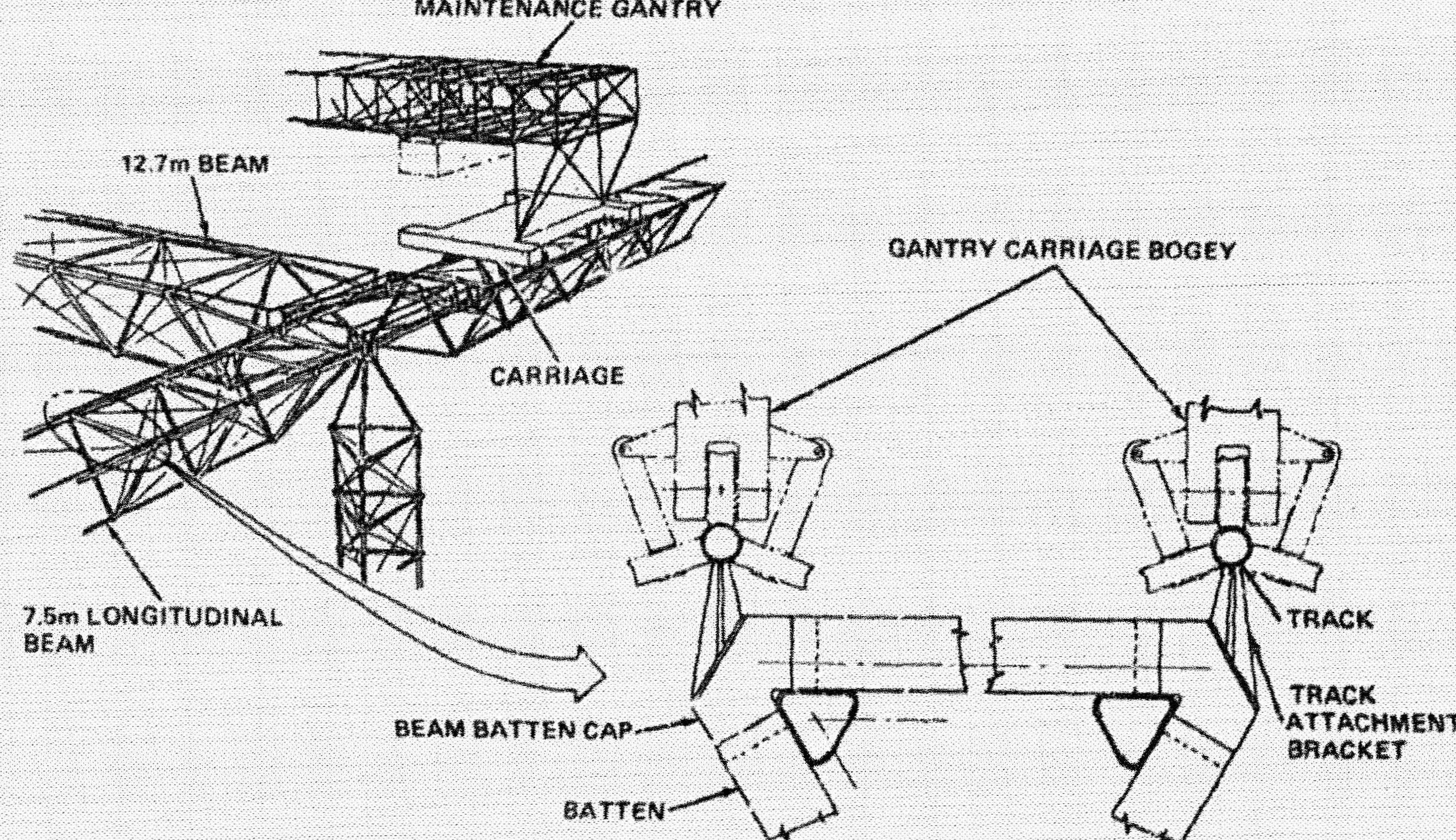
SATELLITE MAINTENANCE TRACK REQUIREMENT

To satisfy the satellite general maintenance requirements, a solar array top surface maintenance system has been proposed. This access system consists of a combination of built-in-tracks, a flying cherry picker, a rotary boom, and some gantries. The built-in-track system, as illustrated on the facing page, adds further requirements to the energy conversion structural arrangement and beam machines. The upper surface triangular continuous longitudinal beams are required to be oriented with a flat side up (as shown) to provide for the mounting of the track system. The tracks are supported by the beam with fittings attached at each beam batten.

This longitudinal beam orientation complicates the use of nodal fittings at the upper surface structural joints, as the vertical and diagonal bracing beams intersect the apex down chord of the beam. Special offset fittings would be required to bypass the chord member.

SATELLITE MAINTENANCE TRACK REQUIREMENT



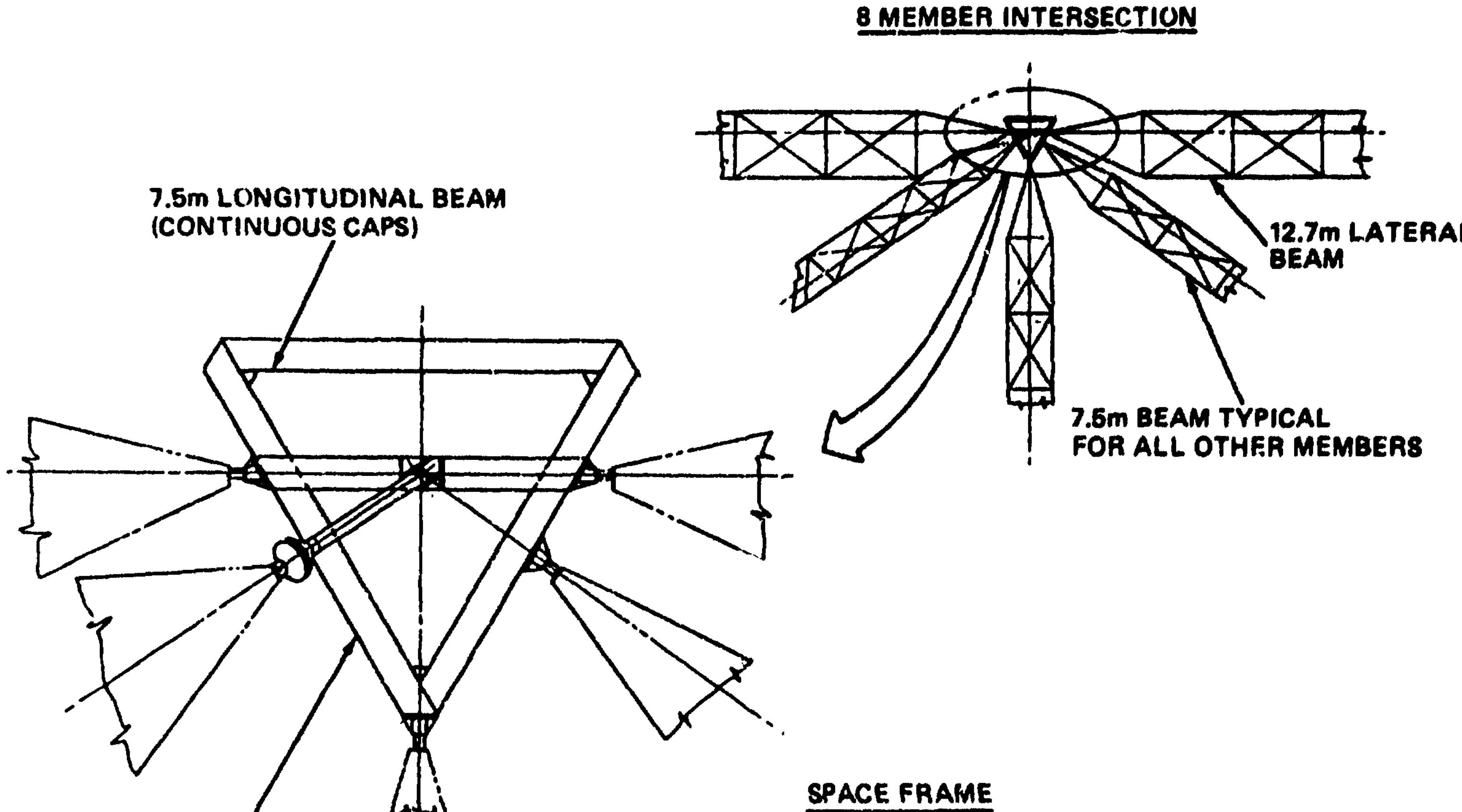
TYPICAL 7.5m LONGITUDINAL BEAMS
& 12.7m LATERAL BEAMS

STRUCTURAL JOINT DESIGN COMPATIBLE WITH END BUILDING CONSTRUCTION

A space frame is used in the assembly of the multi-member structural joints of the energy conversion structure. As shown the frame replaces one set of battens of the longitudinal beam and does not interrupt the continuous chords (caps) of the beam. Pickup points are provided on the periphery of the frame, enhancing access required for the attachment of the lateral, vertical and diagonal bracing beams. These pickup points are located so that the end load in each attaching beam is aligned with the centroid of the continuous longitudinal beam. These frames are also compatible with beam machine fabrication and could be space fabricated or ground fabricated in segments and space assembled. The frame segments are loaded into beam machine supply canisters and the frame assembly becomes an integral operation of the beam machine.

Although the space frame seems attractive at this time, further study is required to determine the effects of introducing torsion in the continuous beam which will result from the eccentricities or misalignment of the attaching beams. Additionally, designs of hybrid nodal spider-type fittings for the joints should be pursued.

STRUCTURAL JOINT DESIGN COMPATIBLE WITH CONTINUOUS LONGITUDINAL BEAM CONSTRUCTION



SPACE FRAME
- CONTINUOUS BEAM UNINTERRUPTED
- BEAMS ATTACH TO PERIPHERY
- FAB (COMPATIBLE WITH BEAMBUILDER) OR ASSEMBLED IN SPACE

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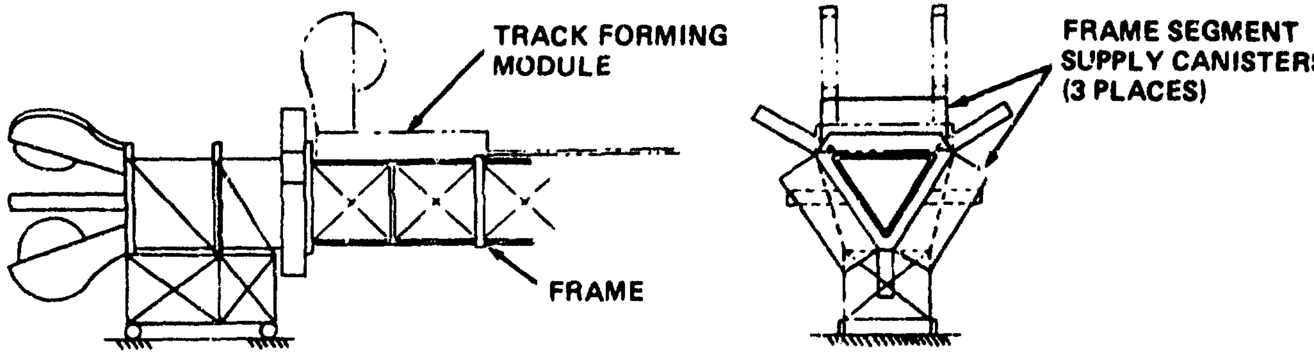
AUTOMATIC BEAM FABRICATION EQUIPMENT UPDATE

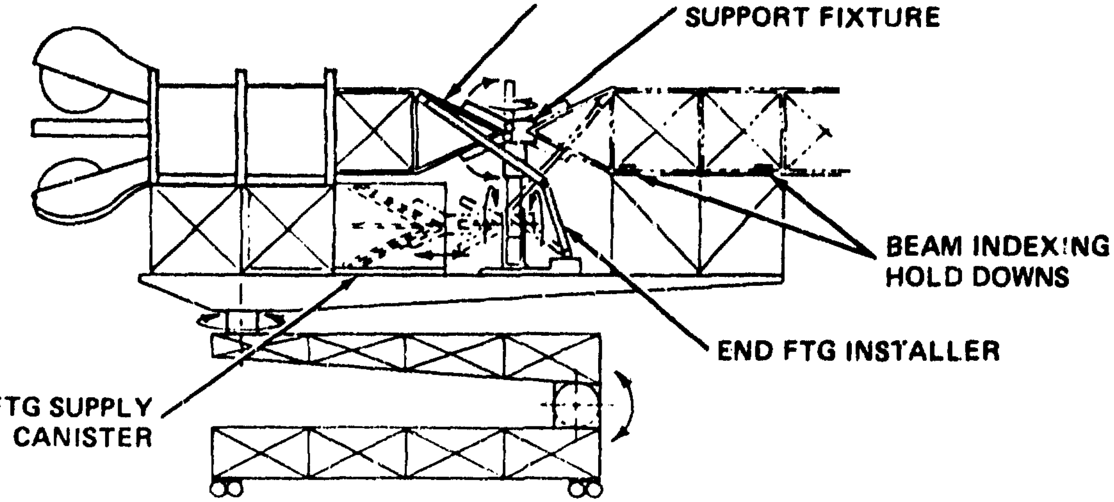
The 7.5 m beam machine is shown equipped with frame-making features. Frame segment supply canisters are mounted at each beam face at cross member attaching stations. Since current track concepts call for supports at each cross member, track attachment will occur after the completed cross members emerge from the beam machine. This requirement dictates the location of the track forming module as shown.

The 7.5 m mobile beam machine is shown with end fitting attachment features. A column mounted end fitting support fixture with movable gripping fingers can rotate to place fittings on either end of a beam. The column swings down as required to clear the emerging beam or pick up an end fitting from the supply canister. The grip is capable of extending to secure and withdraw a fitting from the supply canister. An automatic arm attaches the end fittings to the beam on either end as required. An accessory platform is equipped with holding devices which index the completed beam and position it for installation of the end fitting after it has emerged from the beam machine. The entire platform with beam machine and accessories is capable of 360° swiveling and can be rotated perpendicular to the carriage to provide any required orientation.

AUTOMATIC BEAM FABRICATION EQUIPMENT UPDATE



7.5 m BEAM/TRACK MACHINE



7.5 m MOBILE BEAM MACHINE

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ENERGY CONVERSION BEAM BUILDER REQUIREMENTS

Four basic types of beam machines are required for fabrication use. Two types are synchronized for continuous longitudinal beam fabrication, while the remaining two autonomous types are employed to fabricate lateral, vertical and bracing members. The 7.5 m synchronized and 12.7 m autonomous types operating at the solar array level are equipped to provide track. The remaining two types which do not operate at the solar array level do not have track capability.

ENERGY CONVERSION BEAM BUILDER REQUIREMENTS

TYPE MACHINE	7.5 m SYNCHRONIZED W TRACK	7.5 m SYNCHRONIZED W/O TRACK	12.7 m AUTONOMOUS W TRACK	7.5 m AUTONOMOUS W/O TRACK
USE	UPPER (SOLAR ARRAY) LONGITUDINALS	LOWER LONG BEAMS	UPPER (SOLAR ARRAY) LATERALS	ALL OTHER BEAMS
FUNCTIONS	• FAB 7.5 m CONTINUOUS BEAM W FRAMES & TRK • NOMINAL FIXED • REMOTE CTL	• FAB 7.5 m CONTINUOUS BEAM W/FRAMES • NOMINAL FIXED • REMOTE CTL	• FAB 12.7 m BEAM W/END FITTINGS & TRACKS • MOBILE & GIMBALED • ON BD OPER	• FAB 7.5 m BEAM (VARIOUS LENGTHS) W/END FITTINGS • MOBILE & GIMBALED • ON BD OPER
NO MACHINES	5	5	1	1
FAB RATE	3.5 m/min	3.5 m/min	5 m/min	5 m/min
BEAM MATL CAPACITY	10,800 m	10,800 m	10,700 m	10,200 m
GIMBAL CAPACITY	TBD	TBD	YAW ±90°	YAW ±90° PITCH 90°
TRAVEL	3.5 m/min	3.5 m/min	20 m/min	20 m/min

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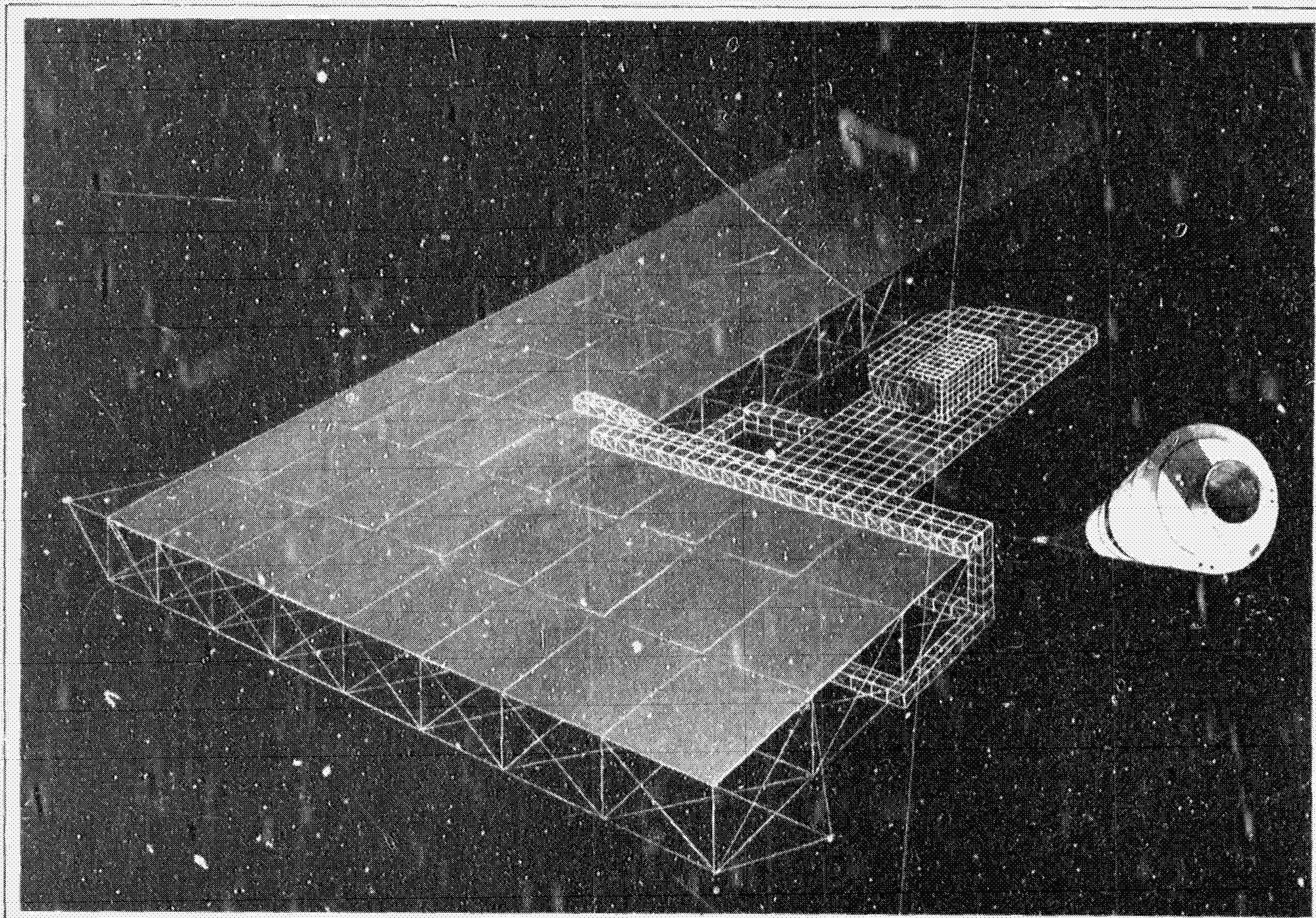
SPS CONSTRUCTION SECOND PASS



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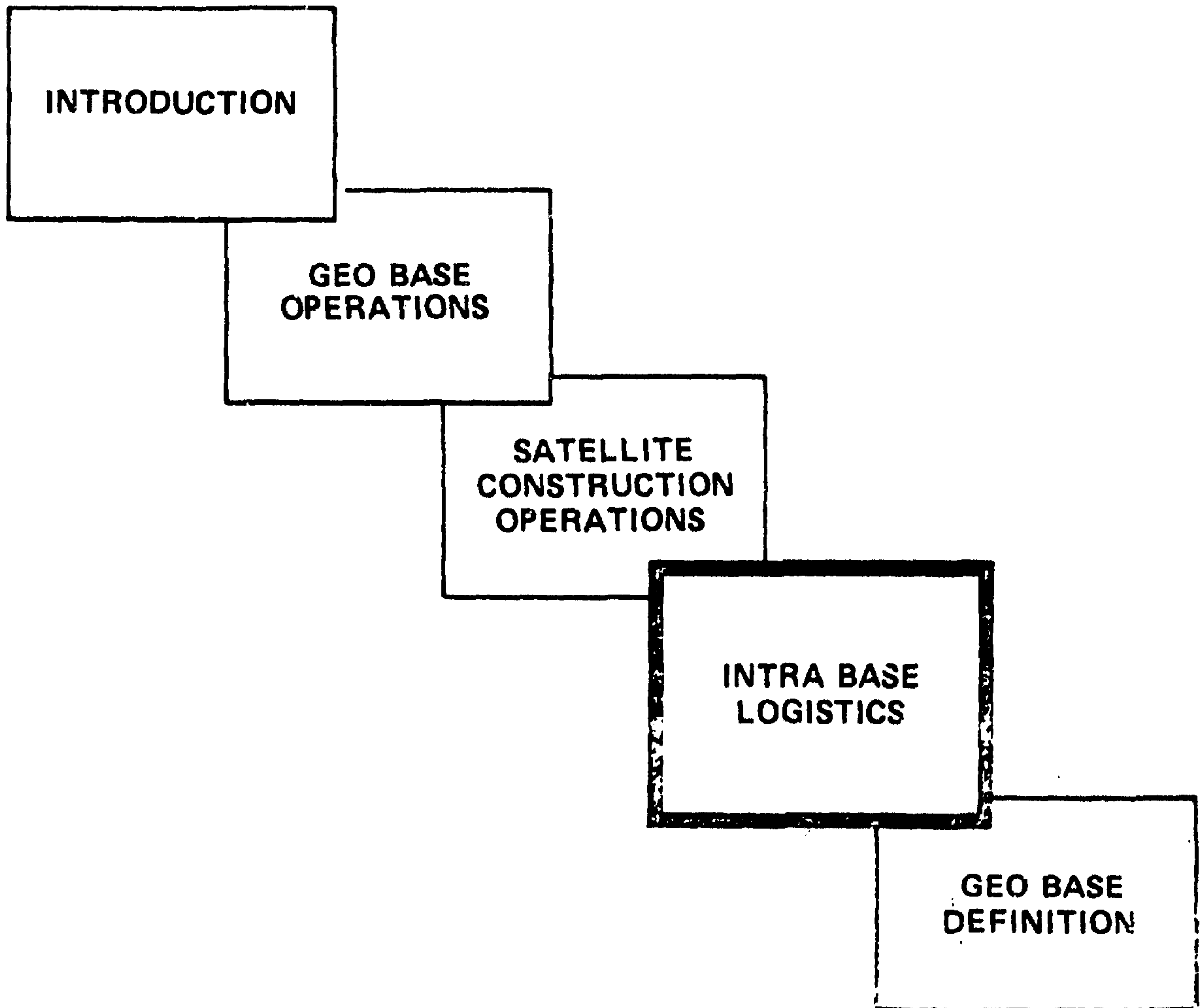
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GEO BASE LOGISTIC SUPPORT REQUIREMENTS

The GEO Base, in addition to building the SPS, must fulfill strenuous logistic support requirements.

Every thirteen days an EOTV will arrive with large Cargo Pallets. A dedicated area must be available at the GEO Base to transfer this material on board in a quick and efficient manner. At the same time, empty pallets have to be removed from the base. As soon as the Cargo Pallets are landed, they have to be moved to an unloading area and processed through the subassembly factory. To accomplish this, an efficient transport system must be available.

The base has to rotate the 827-man crew at planned intervals. All these people have to be housed comfortably and transported to their assigned work stations each day. Each time a new crew is brought up, resupplies must also be provided.

The other function of the base is to serve as a home base for service of all outlying SPS stations. Defective material on the SPSs must be replaced, brought back to the base and reconditioned. The refurbished material is stored until needed as replacement parts on the next visit to the SPS stations.

GEO BASE LOGISTIC SUPPORT REQUIREMENTS

- EOTV CARGO DELIVERY
  - 4000 MT UP & 200 MT DOWN/FLIGHT - EVERY 13 DAYS
  - OPERATE & SERVICE 2 CARGO TRANSFER TUGS
  - DOCK & UNLOAD 10 TO 20 CARGO PALLETS
  - PROVIDE PALLET TRANSPORTERS
- POTV GEO CREW ROTATION
  - ROTATE UP TO 160 PEOPLE/FLIGHT @ 10-DAY INTERVALS
  - MAINTAIN TRANSIENT CREW QUARTERS
  - DOCK 2 POTVs & PROVIDE INTRA-BASE CREW BUSES
- SPS OPERATIONAL MAINTENANCE SUPPORT
  - LOAD/UNLOAD SPS COMPONENT RACKS @ 4½-DAY INTERVALS
  - MAINTAIN RECONDITIONED & DEFECTIVE COMPONENT STORAGE
  - DOCK & SERVICE SPS MAINT FLEET (4 OTVs & 4 PAYLOADS)
  - MAINTAIN COMPONENT REFURB FACILITIES & PROVIDE CREW HABITATS

CARGO DOCKING/UNLOADING CENTER

This area has docking facilities for KTM and Cargo Pallets. Adjacent to this site is the unloading area, bounded by mainline track No. 1 on one side and mainline track No. 2 on the other. Seven (7) sets of 12.7 m tracks interconnect the mainline tracks.

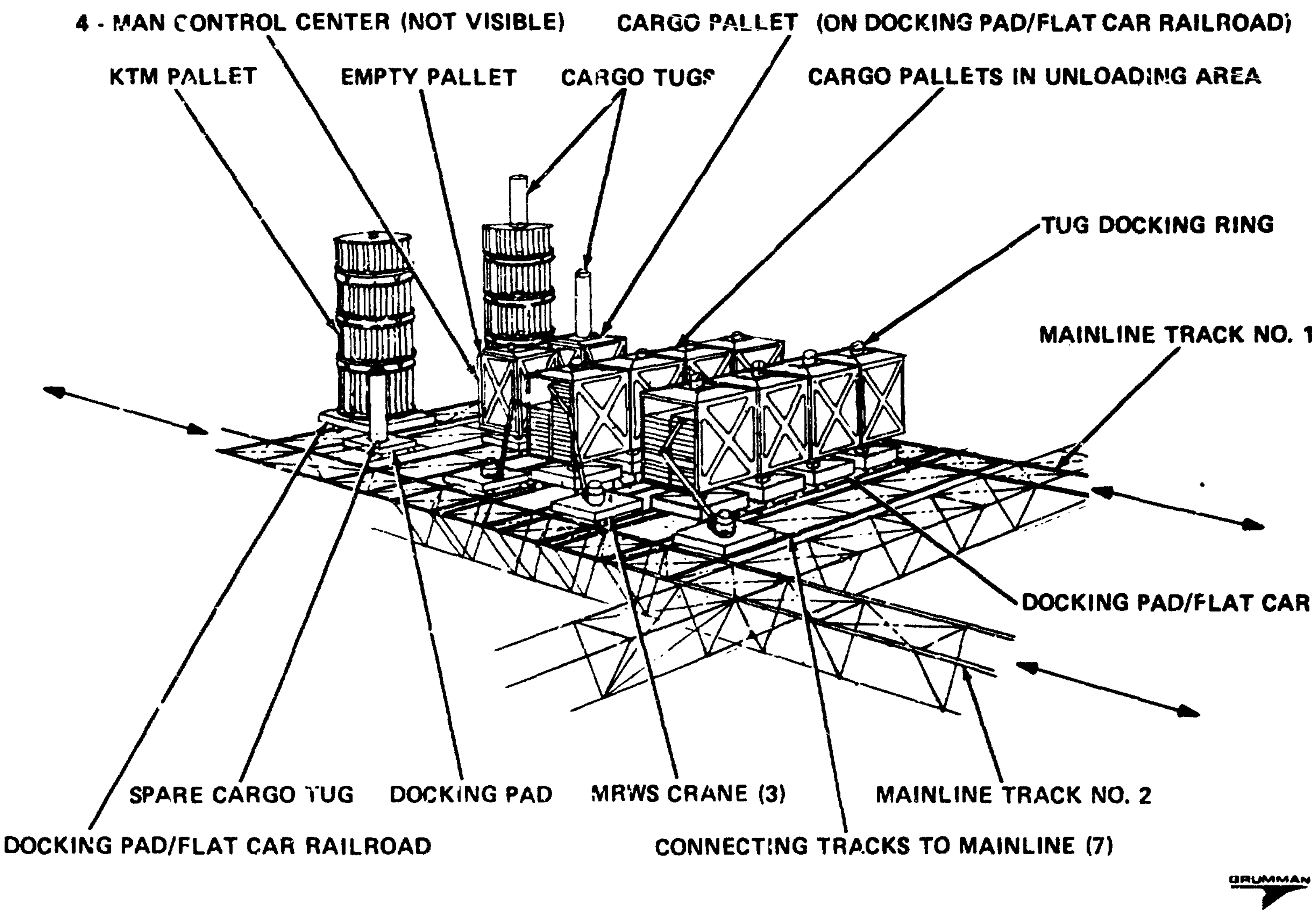
Starting at the left, the first connecting track contains two (2) docking (landing) pads, which are rail mounted, for the docking and launch of KTM Pallets. When these vehicles land, the 3,800 Klystrons in each Pallet are unloaded onto waiting flat cars. As each flat car is filled, it moves to the mainline track and then onto one of the vertical stanchion elevators. The elevator lowers the loaded car down to the appropriate level, then over to the Antenna Facility.

The 12.7 m beam installed to the right of the first connecting track contains two (2) docking pads and a small control center. An OTV Cargo Tug is docked to each pad, one of them being a spare unit. The operational Tug flies over to the parked EOTV where it will pick up, one at a time, the Cargo Pallets for delivery to the factory. A long Spacelab module is located between the two parked Tugs. A crew of four (4) has all the controls and displays necessary to land the KTM and Cargo Pallets on the four docking pads.

The second connecting track contains two (2) docking pads, also rail mounted, for the Cargo Pallets. The top pad is used for landing full Cargo Pallets and the bottom one for lifting off empty Cargo Pallets. In this scenario, the crew in the control center lifts off the parked OTV Tug and flies it toward the EOTV, where it docks to one of the ten (10) Cargo Pallets. This unit is lifted off the EOTV and flown back to the Factory and landed on the upper landing pad. The OTV Tug is then lifted off the docked Pallet and flown down a short distance to the empty Cargo Pallet mounted on the lower landing pad. When attached, it will lift off this assembly and fly it back to the ETOV. The Tug lifts off the returned Pallet and docks to another full Cargo Pallet for delivery to the Factory.

The full Cargo Pallet which was landed on the Factory is moved on its docking pad/flat car to mainline track No. 1. From here it moves laterally to either the 4th or 6th connecting track, where it is placed in the Cargo Storage area. As the Pallet moves forward to the front of the line, it is unloaded by the three (3) MRWS Cranes located on the 3rd, 5th and 7th connecting tracks. The cargo material is loaded onto waiting flat cars located on mainline track No. 2. When the cars are full, they are moved onto the vertical stanchion elevators. The cars are lowered to the appropriate level and either unloaded or stored till empty. As each Cargo Pallet is unloaded, it is moved back to the launch pad area for liftoff back to EOTV.

CARGO DOCKING/UNLOADING CENTER



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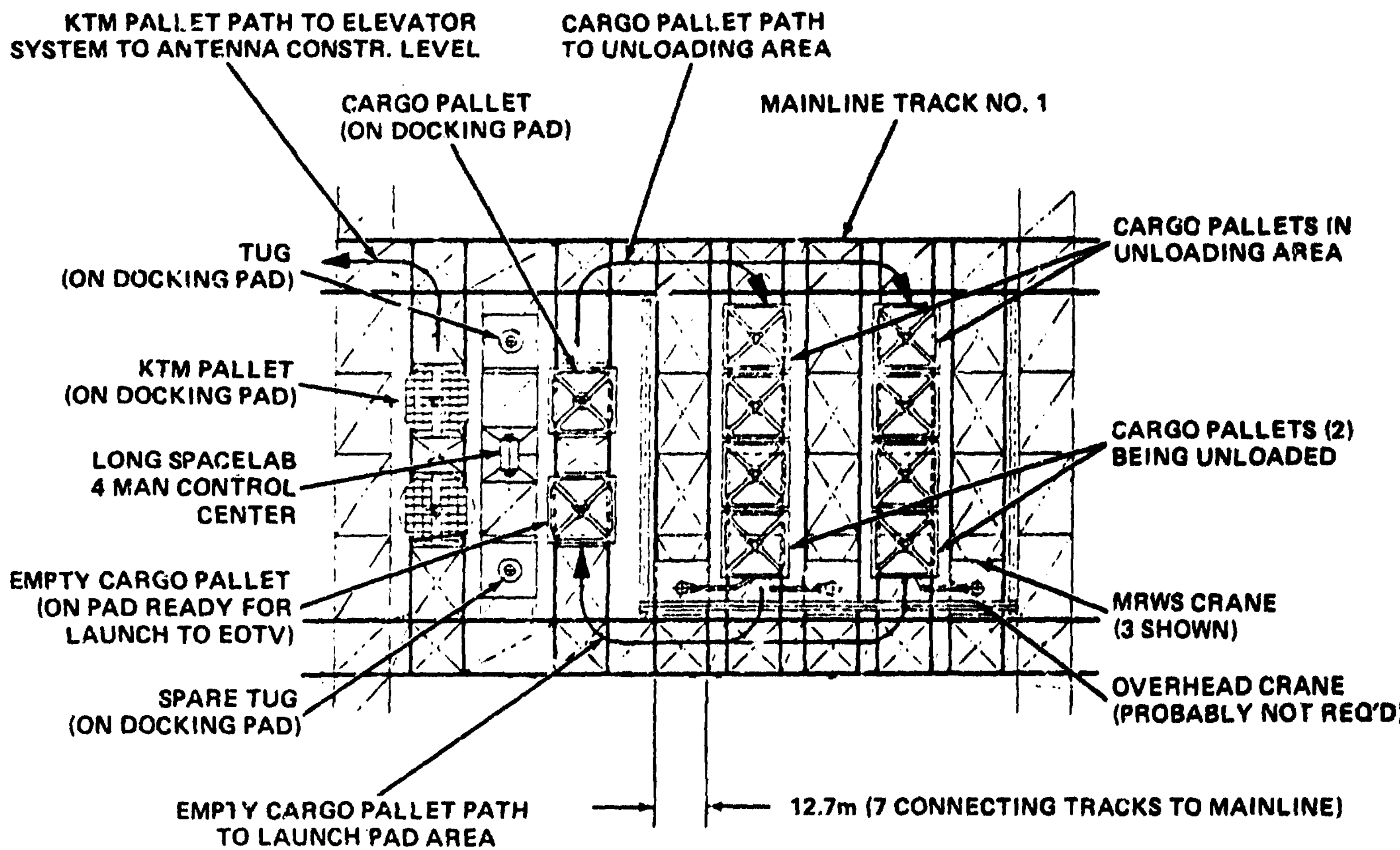
CARGO DOCKING/UNLOADING CENTER (PLANE VIEW)



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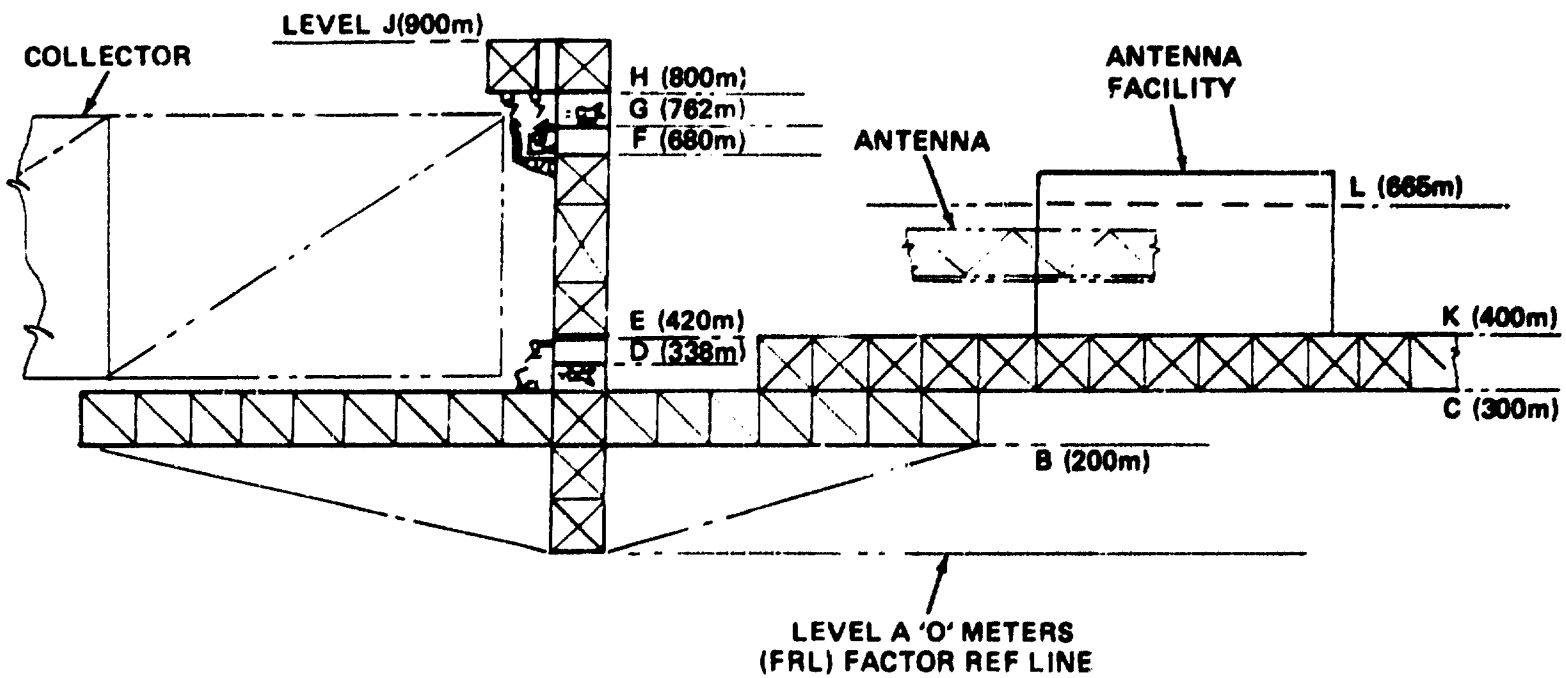
GEO FACTORY LEVEL IDENTIFICATION

The facing page illustration identifies eleven levels of the energy conversion and antenna construction facilities. The levels are identified with letters A through L and their elevations are given in meters. The elevations are taken from the base level A the factory reference line (FRL).

GEO FACTORY LEVEL IDENTIFICATION – BASELINE



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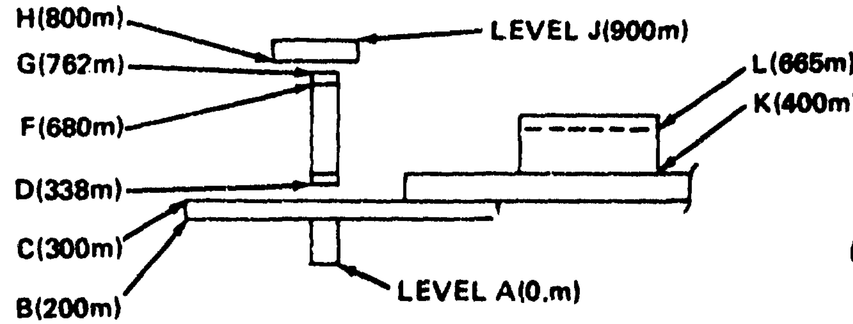
GEO BASE INTERLEVEL MATERIAL TRANSFER REQUIREMENTS

The accompanying chart lists the total weight of material that has to be delivered to the GEO Base for construction of an SPS. It can be seen that over half of the material landed on the base has to be delivered to Level "H" for use in assembling the energy conversion assembly and solar blankets. Two levels were considered as docking areas for delivery of personnel and material. Based on this chart, it is apparent the logistics system is greatly simplified by using Level "J" for the docking area.

GEO BASE INTERLEVEL MATERIAL TRANSFER REQUIREMENTS



LEVEL "J" DOCKING SELECTED

FACTORY LEVEL	CONSTRUCTION OPERATION	TOTAL MAT'L MT	RATE MAT'L USED	INTER LEVEL MASS DISTANCE 10^8 kg-m "B"-DOCK	"J"-DOCK
	ENERGY CONVERSION ASSEMBLY				
H	– SOLAR BLANKET INSTALLATION	23185	725MT/4DAYS	139.1	23.18
G	– STRUCTURE FAB & ASSY	1731	398MT PLUS 42MT/4 DAYS	9.72	2.38
F	– STRUCTURE FAB & POWER BUS INSTL	1845	58MT/4 DAYS	8.86	4.06
D	– STRUCTURE FAB & ASSY	1731	398MT PLUS 42MT/4 DAYS	2.39	9.72
	POWER TRANSMISSION ASSEMBLY				
K	– STRUCT FAB & ASSY & SUBARRAY INSTL	9953	83MT/DAY	19.91	69.67
L	– STRUCT FAB & ASSY & PWR BUS INSTL	2558	21MT/DAY	11.89	24.68
	TOTAL	41000MT		191.87	133.[illegible]9

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INTERLEVEL MATERIAL TRANSFER OPTIONS

Movement of material can be accomplished either on a railed track system or by a Free Flyer. During the construction of the SPS, large quantities of material have to be moved to pre-designated areas at regular time intervals. This type of operation fairly well dictates a semi-automated transportation system. It appears that the railed system can meet these requirements more readily than the Free Flyer system.

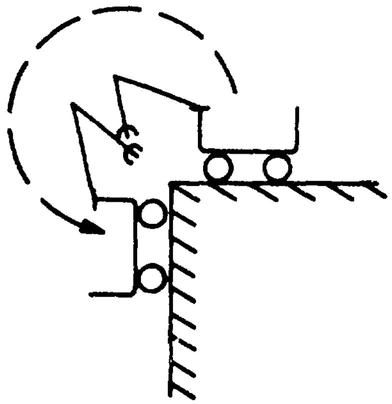
This illustration shows the mainline railroad system on Level "J." All the material and personnel from earth are delivered to the Level "J" area. The rail system depicted can move the people and material on this level quickly and efficiently. Once the material is processed through the unloading depot and subassembly factory, it then has to be moved down to the various construction levels. Three methods have been considered for interlevel transportation. The first requires a vertical rail system at each vertical stanchion. The material in the horizontal flatcar has to be transferred into a waiting flatcar on the vertical track. This method is time-consuming and costly by virtue of additional track and flatcar requirements.

The second method is a horizontal rail system on Level "J" supplemented with vertical elevators at each stanchion. In this scheme, the loaded flatcar is moved out to the waiting elevator platform. The elevator is lowered to the appropriate sublevel where the flatcar is either unloaded or side-railed. The third method is to provide a vertical and horizontal rail system as shown in Scheme 1. The two rail systems are connected by a curved track. In this manner one loaded flatcar can travel from point A to B.

The second and third methods show promise for further study.

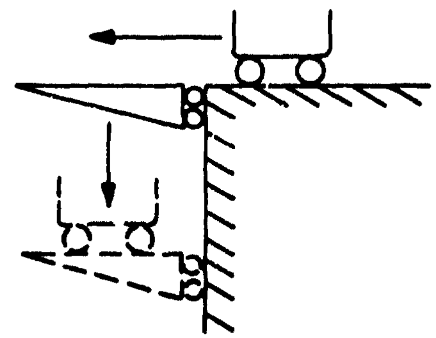
INTERLEVEL MATERIAL TRANSFER OPTIONS

- RAILED TRANSPORTATION



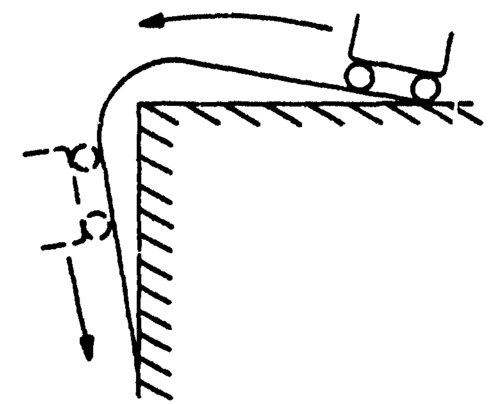
HORIZ & VERT TRACKS
– 2 CARS

- DIFFICULT TRANSFER
- TIME - CONSUMING
- MAN - IN - LOOP REQ'D



HORIZ TRACKS & VERT ELEVATOR
– 1 CAR

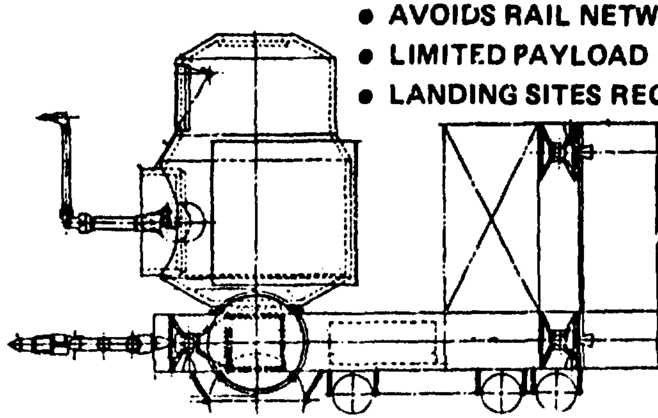
- SINGLE RAILROAD & CAR
- SIMPLIFIED ELEVATORS TO EACH LEVEL
- AUTOMATED



CURVED TRACK
– 1 CAR

- EASY TO OPERATE
- DIFFICULT TO BUILD
- AUTOMATED

- FREE FLYERS
  - AVOIDS RAIL NETWORK
  - LIMITED PAYLOAD
  - LANDING SITES REQ'D



FURTHER
STUDY OF RAILED
& FREE FLYER
LOGISTICS SYSTEM
REQUIRED

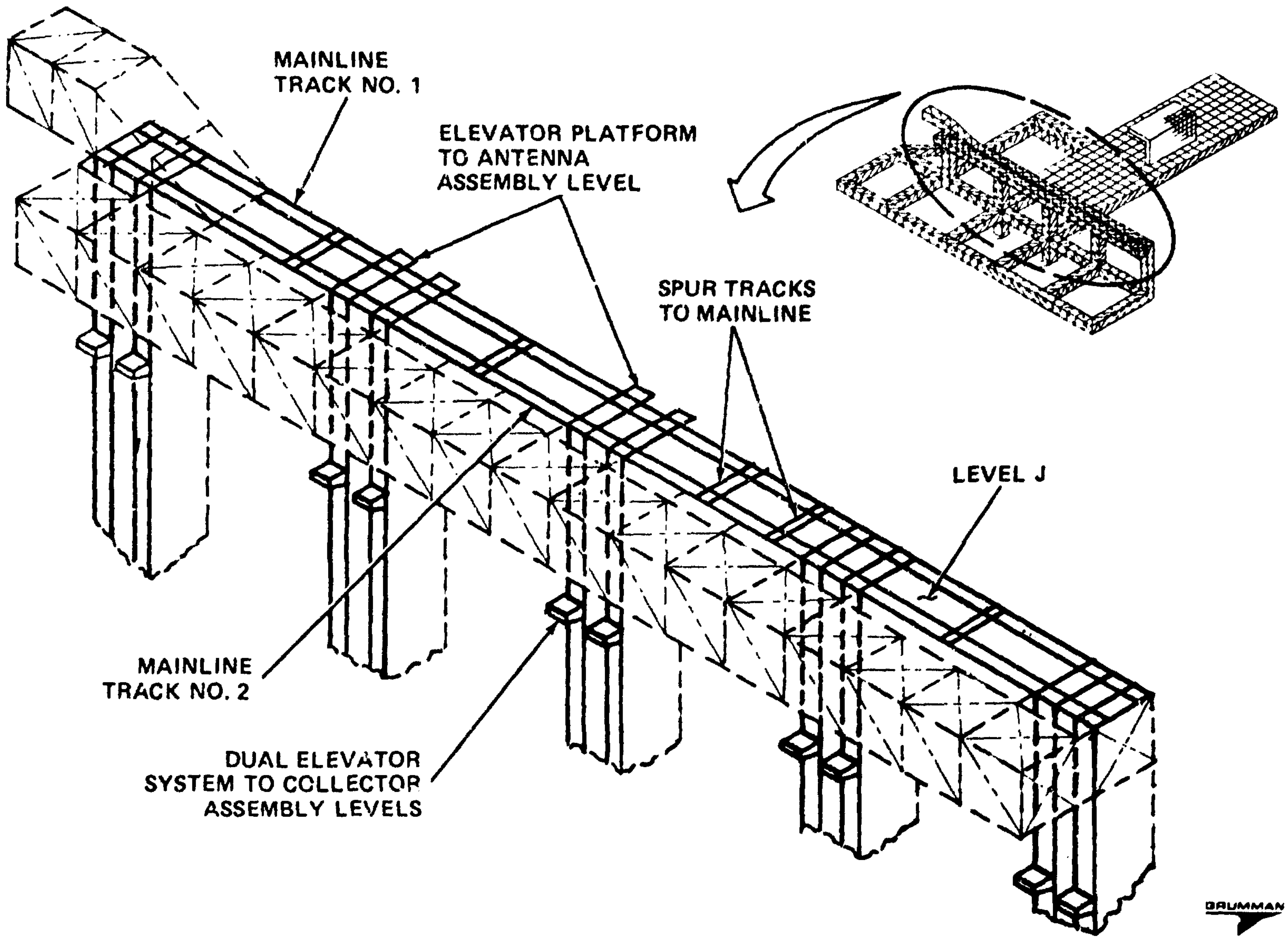
1079-028D

GEO BASE TRANSPORTATION SYSTEM

This illustration depicts a railroad system that encompasses all areas on Level "J". It is apparent that the key to a successful operation is an efficient transportation system for material and personnel movement. For construction of the Solar Collector and Antenna, huge quantities of material and personnel have to be delivered throughout the Factory. After the material and personnel have been landed on the Factory, they must be transported quickly to their next facility. This constant flow of material dictates that the area selected for this operation be clear of the construction area. It must also provide a transportation system that can move material in both the horizontal and vertical planes.

Level "J" has been chosen as the surface to which materials and personnel will be delivered. A railroad system surrounding all elements on this level will quickly move material and personnel to their next location in the Factory. An elevator network is shown at each stanchion for vertical movement of material to the lower levels. In this manner, the railroad can move on the level "J" 12.7 m railroad tracks to the designated vertical stanchions of the Factory. The car will then move onto the elevator lift and proceed down to its designated level. At this point the car can either be unloaded or moved off the elevator to a storage area; this requires further study.

GEO BASE TRANSPORTATION SYSTEM

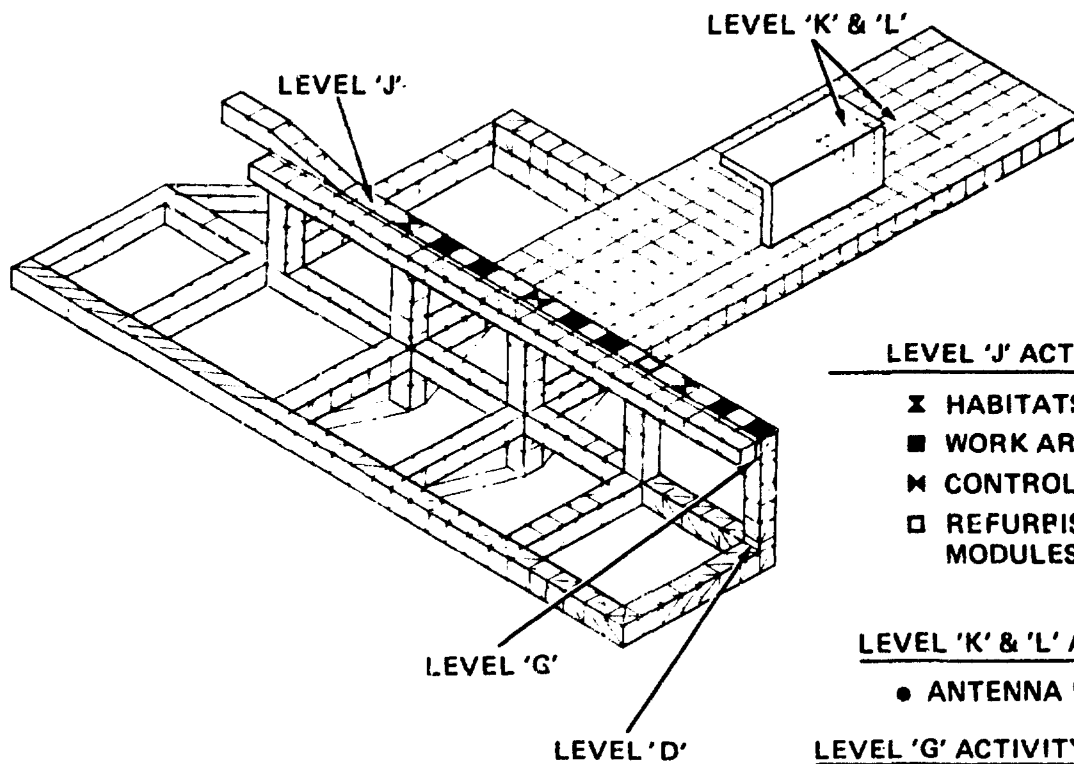


1079-020D

GEO BASE PERSONNEL DISTRIBUTION DURING ONE SHIFT

The accompanying sketch illustrates the distribution of personnel during a typical work shift. Approximately five (5) people are located in cherry pickers at Level "D" working on the Solar Collector. Another eleven (11) people are located in various assembly devices at Level "G," working on the collector assembly and energy conversion assemblies. Eighteen (18) people are working on the antenna and are far away from the central home base. The remainder of the people are located throughout Level "J". Five hundred (500) people are located in the eight (8) Habitats. They are either off duty or working within these Habitats. Eighty-five (85) people are working in the Control Center; all facets of the GEO Base and SPS are controlled from this area. The Refurbishment Modules house one hundred forty-three (143) people.

GEO BASE PERSONNEL DISTRIBUTION DURING ONE SHIFT



LEVEL 'J' ACTIVITY	PEOPLE/SHIFT
⧗ HABITATS	500
■ WORK AREAS	85
⧓ CONTROL CENTER	65
□ REFURBISHMENT MODULES	143
LEVEL 'K' & 'L' ACTIVITY	
• ANTENNA FACILITY	18
LEVEL 'G' ACTIVITY	
• ENERGY CONVER ASSY	11
LEVEL 'D' ACTIVITY	
• COLLECTOR ASSY	5

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1079-027D

GEO BASE PERSONNEL TRANSFER CONCEPTS

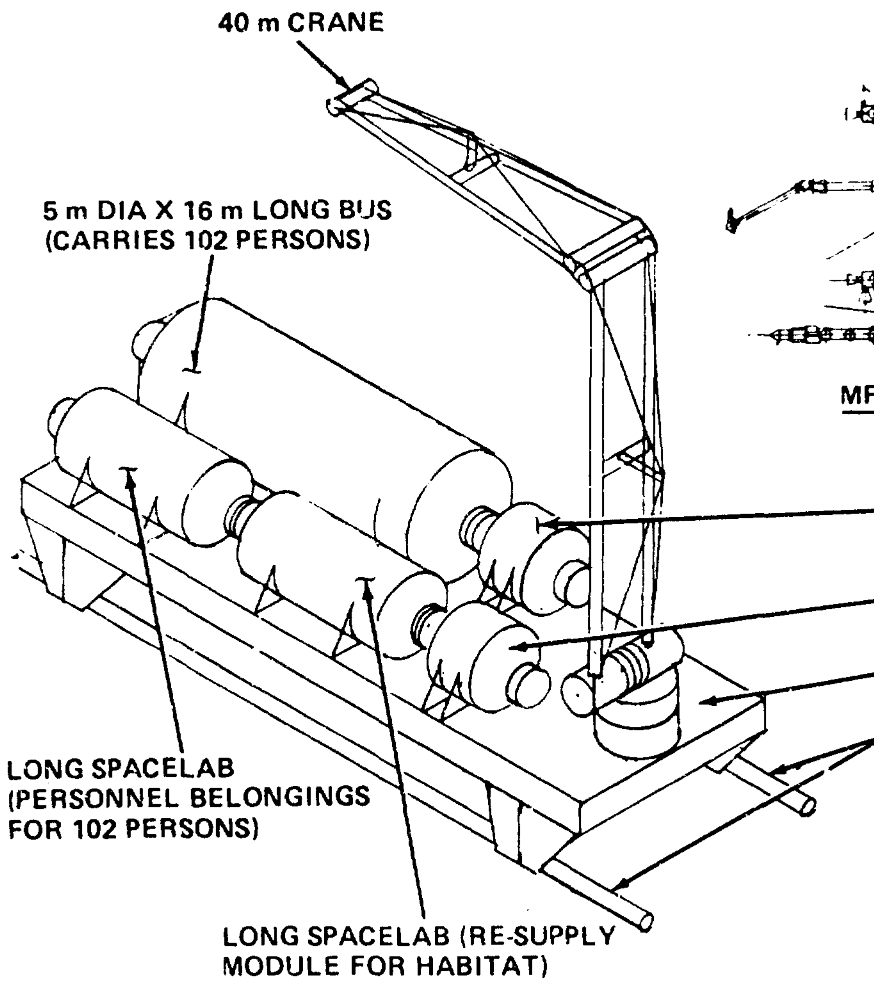
Personnel can move about the GEO Base using three different modes of transportation. Quick and direct movement can be accomplished using a MRWS type of free flyer. This vehicle can carry two people and limited hardware to almost any location on the Base or Satellite. The crew can work at the site while in shirt sleeve attire inside the MRWS. Some work tasks will require that the crew get into close areas that are inaccessible by other means. In this mode the crew member will don a GEO EMU and MMU and traverse short distances to the work site.

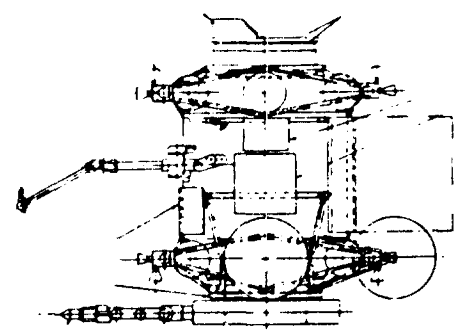
For movement of large numbers of people, the railed bus is used. The flatcar Bus Transporter operates on the 12.7 meter track system, providing movement of people and supplies. The Transporter shown is sized to accommodate the following:

- o A 5 m dia x 16 m long module – This module serves as a bus for movement of 102 people from the OTV landing site to the habitat centers
- o A short Spacelab attached to the end of the bus. This module is used to transfer approximately ten (10) people at a time from the landed POTV to the bus and from the bus to the interim quarters module.
- o Two long and one short Spacelab modules. One long module contains all personal belongings of the fresh crew (102); it was packed on earth prior to launch into space. The other two (2) are replacement modules for those attached to the four (4) habitats
- o A 40 m crane. This device is used to move the transported modules from the bus to the modules.

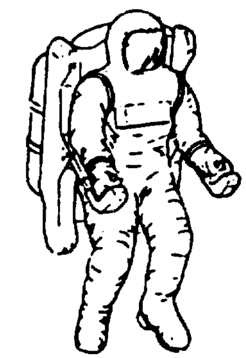
The Bus Transporter can reach the berthing ports on all five (5) modules while moving on mainline tracks No. 1 and No. 2. If another vehicle has to pass by, the Bus Transporter can move off onto the connecting track. Other scaled-down Bus Transporters can be provided to move small crew sizes to the various work sites.

GEO BASE PERSONNEL TRANSFER CONCEPTS





MRWS FREE FLYER



SUITED ASTROWORKER WITH MMU

FURTHER STUDY REQUIRED ON SMALL (2-6) AND MEDIUM (10-24) PERSON BUS TRANSPORTATION

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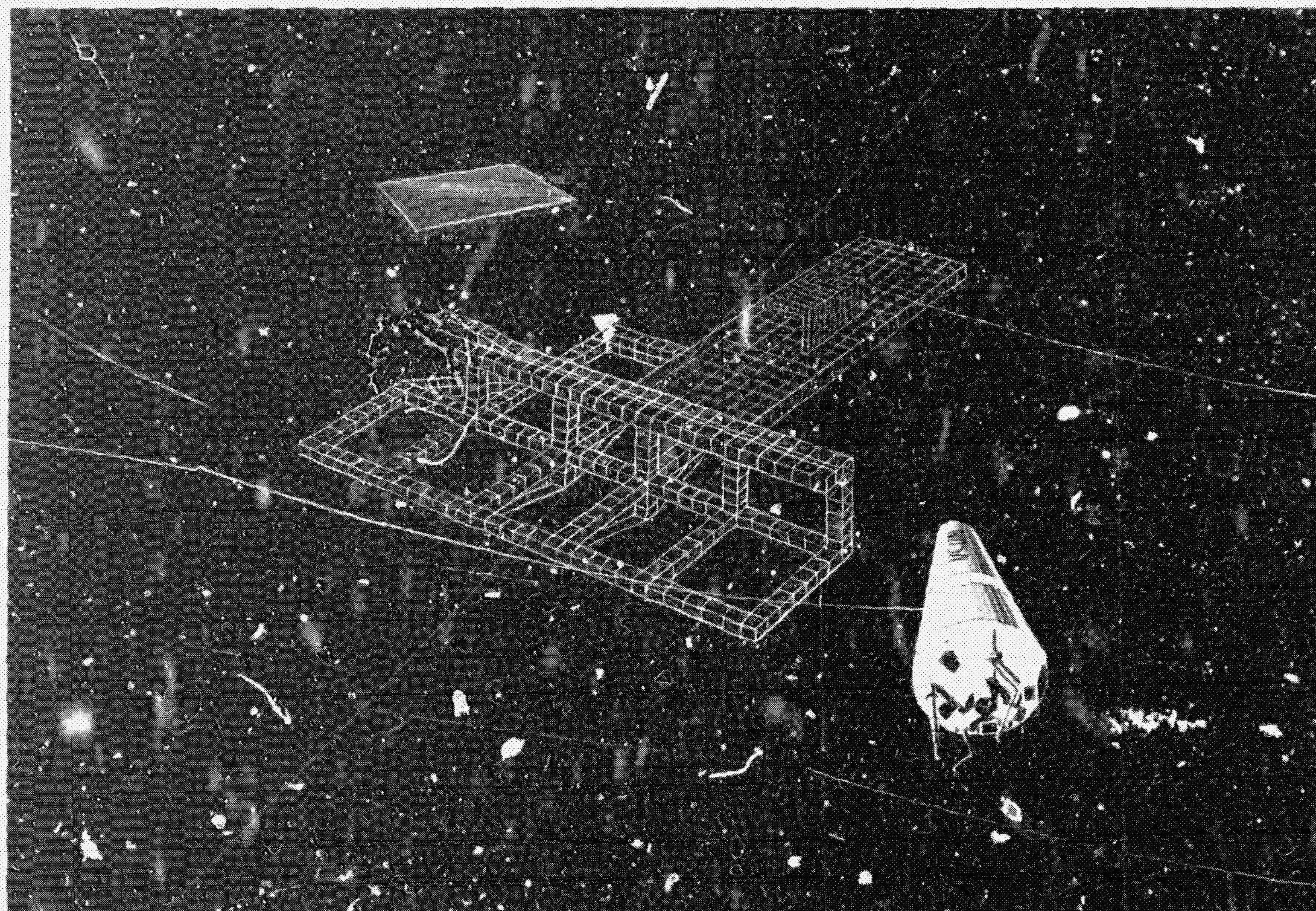
SPS CHECKOUT & BASE TRANSFER



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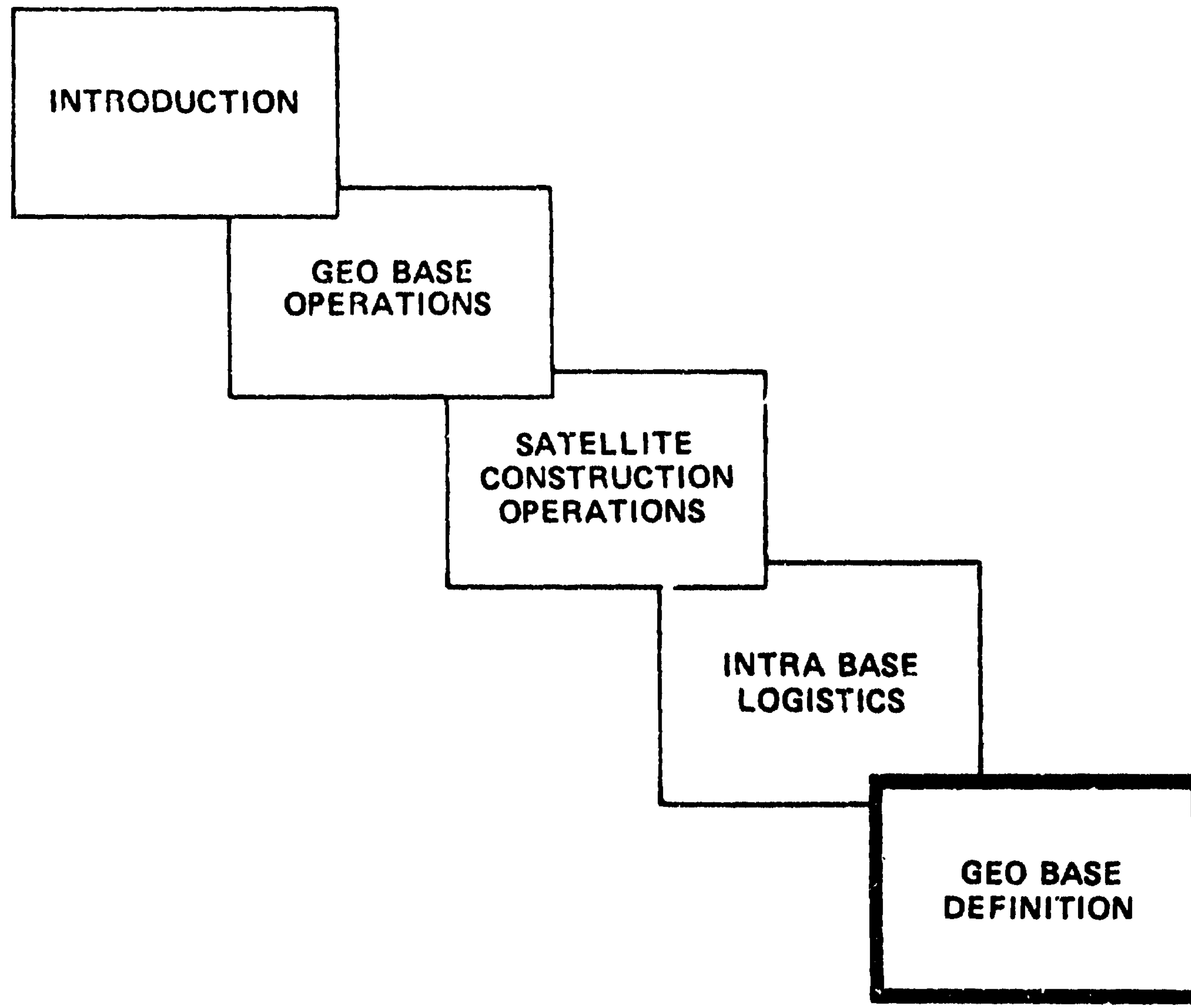

INTRODUCTION
GEO BASE OPERATIONS
SATELLITE CONSTRUCTION OPERATIONS
INTRA BASE LOGISTICS
GEO BASE DEFINITION

1079-05D

GEO BASE SYSTEM REQUIREMENTS

Top level requirements that established the design and operations of the SPS are shown opposite. These are extracted from Phase 1 of the study and guide the definition of all other requirements.

GEO BASE SYSTEM REQUIREMENTS

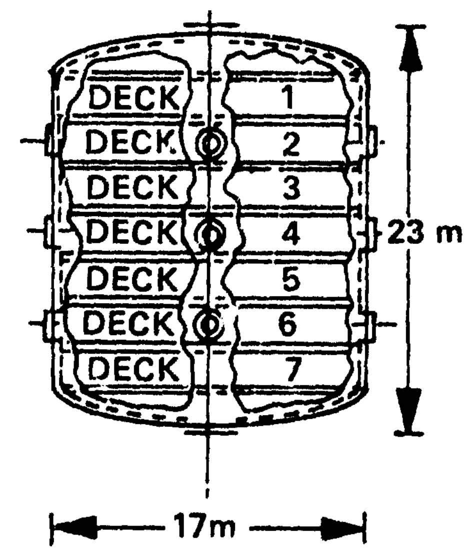
- CONSTRUCT ONE 5 GW SPS WITHIN 6 MONTHS ±5%
- ENERGY CONSERVATION & MICROWAVE POWER CONSTRUCTION FACILITIES CONTIGUOUS
- CONSTRUCTION APPROACH:
  - ENERGY CONVERSION – TWO PASS LONGITUDINAL BUILDUP
  - MICROWAVE POWER – ELEVEN ROW LATERAL BUILDUP
- DESIGN LIFE: 30 + YEARS
- DOCKING & OFFLOADING SYSTEM FOR POTV, CARGO TUG & OTV
- OPERATIONAL AREAS FOR: COMMAND & CONTROL MODULES, CARGO WAREHOUSING, SUBASSEMBLY FACTORIES, CREW & WORK MODULES, BASE MAINTENANCE, OTV MAINTENANCE, EOTV MAINTENANCE, OPERATIONAL SPS MAINTENANCE & TRAINING
- BASE LOGISTIC VEHICLES & TRACK NETWORK
- CONSTRUCTION ACCURACY & QUALITY
- BASE ATTITUDE CONTROL, STATIONKEEPING, LONGITUDINAL TRANSFER CAPABILITY

CREW MODULE GENERAL REQUIREMENTS

Some of the more important requirements used to design the crew module are listed here. The first four requirements establish the size and interfaces of the crew modules. Interior accommodations obviously must be designed for zero g operation. However, to prevent crew disorientation, they should all be designed to a common reference. One-g was selected, as this facilitates ground operations and is satisfactory for space activities. Crew mix was based on the Navy projection for support ships.

CREW MODULE GENERAL REQUIREMENTS

- SIZE (17m DIA X 23m LONG) COMPATIBLE WITH HLLV
- ACCOMMODATIONS FOR 100 PEOPLE
- DESIGN LIFE: 30 + YEARS
- BERTHING/DOCKING/AIR LOCK COMPATIBLE WITH CREW BUS & LOGISTICS & MODULE
- STRUCTURAL ATTACHMENT TO BASE
- DESIGN FOR ZERO G OPERATIONS
- INTERIOR LAYOUT ONE G
- CREW 75% MALE, 25% FEMALE
- METEOROID & SOLAR STORM RADIATION PROTECTION



CREW MODULE

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1079-056D

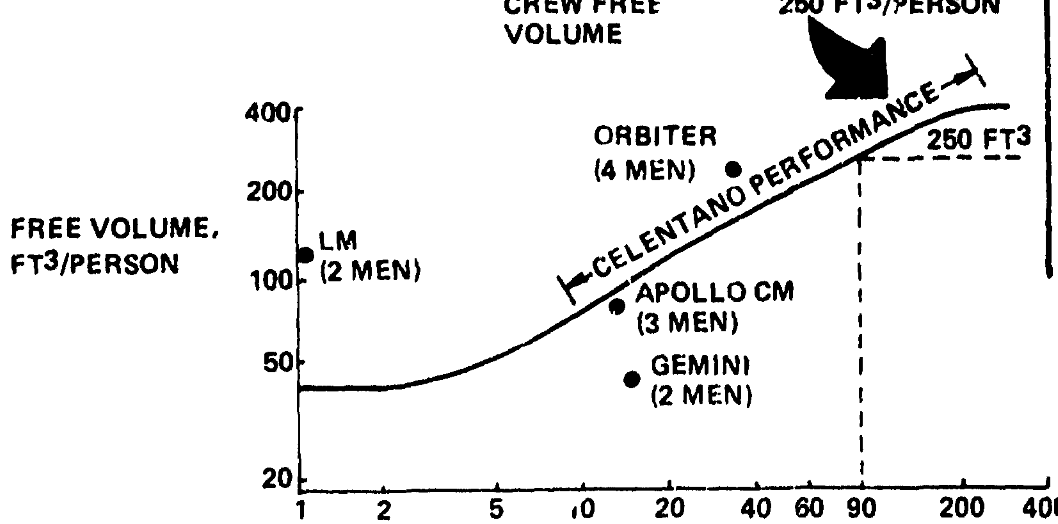
CREW MODULE SUBSYSTEM REQUIREMENTS

Each crew module operates almost independently except for primary electrical power and orbital attitude, which is provided by the base. Emergency power, environmental control, life support and information subsystems are self-contained within each module. Accommodation requirements are based on government and industry studies. Hatches are sized to permit transfer of equipment and are generous for IVA. The environmental control subsystem operating pressure is stated as nominal earth value. However, it could be operated at a lower value (i.e. 10 PSIA, maintaining O_2 partial pressure) thereby possibly reducing structured requirements, and eliminating prebreathing requirements, should emergency EVA be required.

CREW MODULE SUBSYSTEM REQUIREMENTS

- POWER
  - PRIMARY, BASE - SUPPLIED
  - EMERGENCY, SELF - CONTAINED
- ACCOMMODATIONS
  - SKYLAB - TYPE SLEEP COMPARTMENT
  - VOLUME

RECREATION	50 FT^3/PERSON
LAUNDRY	13 FT^3/PERSON
STORAGE	13 FT^3/PERSON
MULTI - PURPOSE ROOM	190 FT^3/PERSON
CREW FREE VOLUME	250 FT^3/PERSON



- ENVIROMENTAL CONTROL
  - 2 GAS, 14.7 PSI, SELF-CONTAINED
- STRUCTURE
  - PRIMARY HATCH 1.5 m DIA, SECONDARY HATCH 1.0 m DIA
  - REDUNDANT PRESSURE SEAL DOORS
  - REDUNDANT EXITS FROM CLOSED VOLUMES
- LIFE SUPPORT
  - WATER RECOVERY
  - WASTE MANAGEMENT
  - PERSONNEL HYGIENE
  - DRIED & FROZEN FOOD
- INFORMATION
  - INTERCOMMUNICATIONS
  - EXTERNAL COMMUNICATIONS
  - DATA PROCESSING
  - CONTROLS & DISPLAYS

GRUMMAN

1079-057D

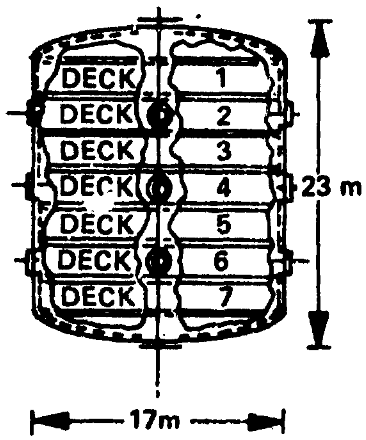
GEO CONSTRUCTION BASE – 100 MAN HABITAT

This illustration depicts a domed end cylinder housing 100 crew members with dedicated work stations. The pressure shell diameter is 16.5 m and the external diameter is 17.0 m. A nominal 0.25 m has been tentatively allotted for thermal insulation, radiation protection and radiator wraparound functions. (No work has been done in these areas to date.) The pressure vessel is 23.0 m long. Seven decks have been provided, each having a 2.2 m floor to ceiling height. The structure between each deck is 0.3 m thick, providing volume for installation of wiring, ducting, lighting, insulation, etc. Decks 2 and 6 have two (2) berthing ports located 90° to each other, while Deck 4 has only one (1) port. These berthing rings are configured to mate with berthing ports on Spacelab-type modules. The attached Spacelab modules provide the services and re-supplies to keep the modules operational. Larger diameter berthing or docking rings are located at each dome end for mating with the base structure, another module or the transportation delivery vehicles (HLLV or EDTV). Each deck contains 16 to 18 viewing windows around its periphery.

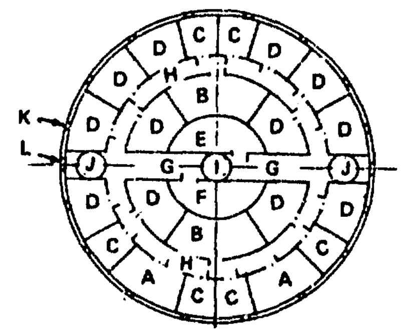
One possible arrangement for accommodating the SPS GEO Base 400-man construction crew is shown by the crew habitat complex on the following pages. Adjacent modules are interconnected with flexible tunnels mated to the berthing hatches on Decks 2, 4 & 6. In this manner, there are at least six ways in and out of each module (total of 12 tunnels). Deck 2 has a short Spacelab-type module affixed to it for use as a 4-6 man airlock. Another short Spacelab is provided for use as a transfer vessel from the large volume habitat to the smaller volume closed cherry picker, bus, free flyer or crane. Deck 4 has one berthing ring for attachment of a long Spacelab module. This module can provide a 90 day food supply for 100 persons. Deck 6 has two berthing rings for attachment of two short Spacelabs. One module contains tankage to re-supply the expendables, while the second module is configured to accept waste material which is compacted into 26-inch cubes. The four large berthing rings on the bottom mate with facilities on the space base. The four large berthing rings at the top of the dome end can be used for emergency docking of HLLV, PLV or OTVs, if needed

Decks 1, 3 and 7 have been allotted for the living quarters for 100 crew members, both male and female. Deck 1 is configured to house the management-type personnel in 16 various sized one and two men staterooms for a total of 24 people. A large waste management compartment and personal hygiene compartment are provided to handle the occupants on this deck. Deck 3 has four staterooms and 18 crew quarters to house 36 persons. It also contains a W/M and personal hygiene compartment. Deck 7 has 24 crew quarters, a W/M and personal hygiene compartment to accommodate 40 people. The density factor of each deck is varied according to job title on board the space base. Providing for more than 100 people in this size module is not recommended.

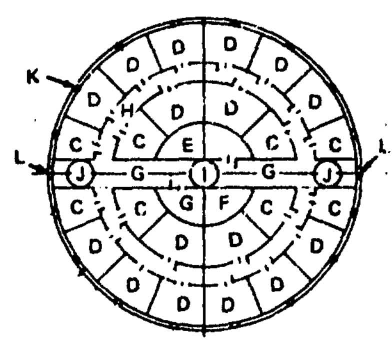
GEO CONSTRUCTION BASE - 100 MAN HABITAT



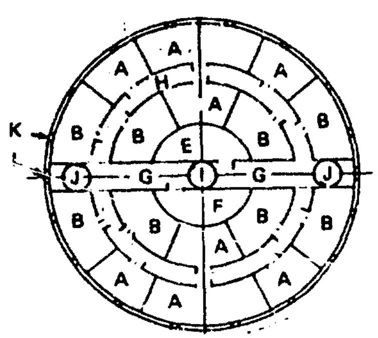
CREW MODULE



DECK 3
CREW QUARTERS



DECK 7
CREW QUARTERS



DECK 1
CREW QUARTERS

HABIT AREAS:

A. ONE-PERSON STATEROOM
B. TWO-PERSON STATEROOM
C. ONE-PERSON CREW QUARTER
D. TWO-PERSON CREW QUARTER
E. WASTE MANAGEMENT
F. PERSONAL HYGIENE
G. CENTRAL PASSAGEWAY
H. TORUS AISLEWAY
I. THRU-DECK ACCESS
J. INTERDECK ACCESS
K. CABIN WINDOWS
L. VIEW WINDOWS

GEO CONSTRUCTION BASE – 100 MAN HABITAT (CONT'D)

Deck 2 contains a control center. A total of 25.44 square meters of displays and controls has been provided to monitor space base and module parameters. The controls need not be duplicated in each of the four modules, but should be overlapped. In the event of a module shutdown, control of the base should still be possible by virtue of the instrumentation remaining in the other three modules. A large room is provided for all facets of EVA hardware.

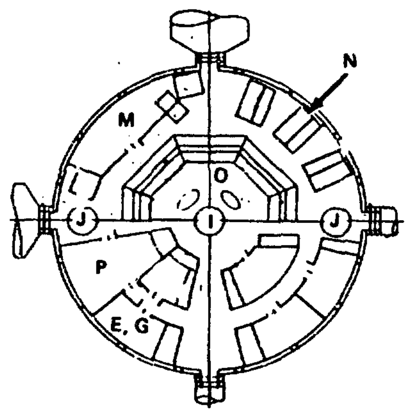
Deck 4 has been arranged to accommodate dining facilities for 60 people at one sitting. The food serving center contains micro-ovens for heating the food, and is the area where the food is dispensed to the diners, cafeteria style. The return rack is the area where used dishes and food are placed. Compactors and dishwashers are located here. Up to 100 people can also be accommodated in Deck 4, when used as a radiation shelter.

Deck 5 is the recreational/physical fitness/services area. The central area is 6 m in diameter and serves as a lounge area. From this lounge, access can be obtained to the snack bar barber shop, post office, chapel, theatre, library, gym and recreation area, and sick bay/dentist areas.

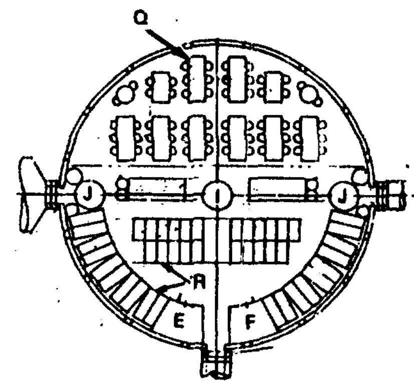
Deck 6 contains tanks for storage of expendables and three large rooms for subsystem equipment and hardware. The fourth quadrant contains storage for waste bales and an area for agricultural study.

Each deck is accessible to the adjacent deck via three (3) 1.5 m diameter openings. In general, the decks have a 1.5 m wide central aisle passageway and a torus aisleway 1.0 m wide.

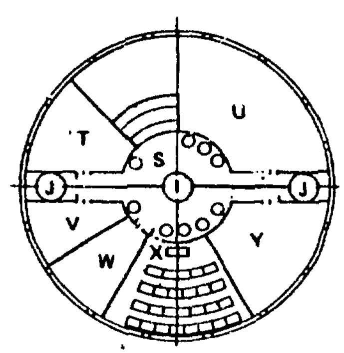
GEO CONSTRUCTION BASE - 100 MAN HABITAT (CONT'D)



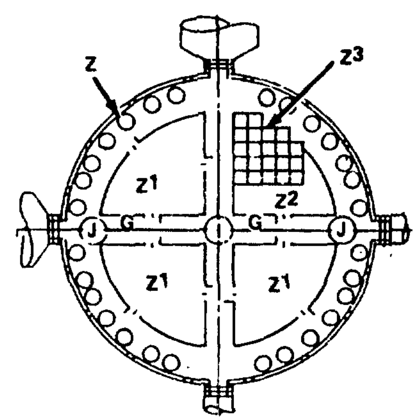
DECK 2
CONTROL CENTER/SUBSYSTEMS



DECK 4
GALLEY/DINING AREA/STORM SHELTER



DECK 5
RECREATION/PHYSICAL
FITNESS/SERVICES



DECK 6
EXPENDABLES/SUBSYSTEMS

HABIT AREAS:

- M. EMU/EVA PREP ROOM
- N. COMPUTER RACKS
- O. CONTROL CENTER
- P. CONFERENCE ROOM
- Q. DINING AREA (60 PERSONS)
- R. FOOD STORAGE
- S. LOUNGE
- T. LAUNDRY/SUPPLIES
- U. RECREATION/GYMN
- V. BARBER SHOP/POST OFFICE
- W. LIBRARY/STUDY
- X. THEATER/CHAPEL
- Y. SICK BAY/DENTIST
- Z. EXPENDABLES
- Z1. SUBSYSTEMS
- Z2. AGRICULTURAL STUDY
- Z3. COMPACTED WASTE

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1079-040D

CREW MODULE WEIGHT SUMMARY

This table presents a summary of the current Grumman weight estimate for the crew module. It shows weights for crew modules in both earth orbit and geosynchronous orbit.

The structural weight has been estimated based on an aluminum structure of cylindrical shape 16.5 m in diameter and 17.8 m long, capable of supporting 14.7 psi internal pressure. Numerous decks divide the cylinder. Two large access/egress ports are located on either end, and 12 berthing ports are located around the circumference. Partitions and equipment mounting weights have also been estimated.

No shielding is required for LEO. A "storm shelter" approach has been used for GEO. A 7.2 m cylindrical band around the module protects one deck from solar storms. The storm shelter provides 20 grams/cm^2 shield thickness protection.

Environmental control subsystem weights are based on 100% redundant systems capable of sustaining 100 men.

Consumables for 100 men for 90 days have been estimated. In addition, a weight growth/contingency factor of 33% has been maintained. All other subsystem weights remain the same as those listed in Boeings Phase 1 SPS study Final Report, Volume III Reference System Description 17180-25037-3.

CREW MODULE WEIGHT SUMMARY

SUBSYTEM	WEIGHT, kg X 10^{-3} LEO	GEO
STRUCTURE	69.7	69.7
ENVIRON PROTECTION (20 g/cm^2)	0	68.3
ELECTRICAL POWER SUPPLY	5.0	5.0
ENVIRON CONTROL/LIFE SUPPORT	22.8	22.8
CREW ACCOMMODATIONS	11.0	11.0
COMMUNICATIONS/DATA HANDLING	6.0	6.0
GUIDANCE & CONTROL	0	0
PROP/REACTION CONTROL	0	0
SPECIAL EQUIPMENT	0	0
SUBTOTAL	114.5	182.8
GROWTH/CONTINGENCY (33%)	37.8	60.3
TOTAL DRY	152.3	243.1
CONSUMABLES (90 DAYS)	43.9	43.9
TOTAL	196.2	287.0

GRUMMAN

1079-046D

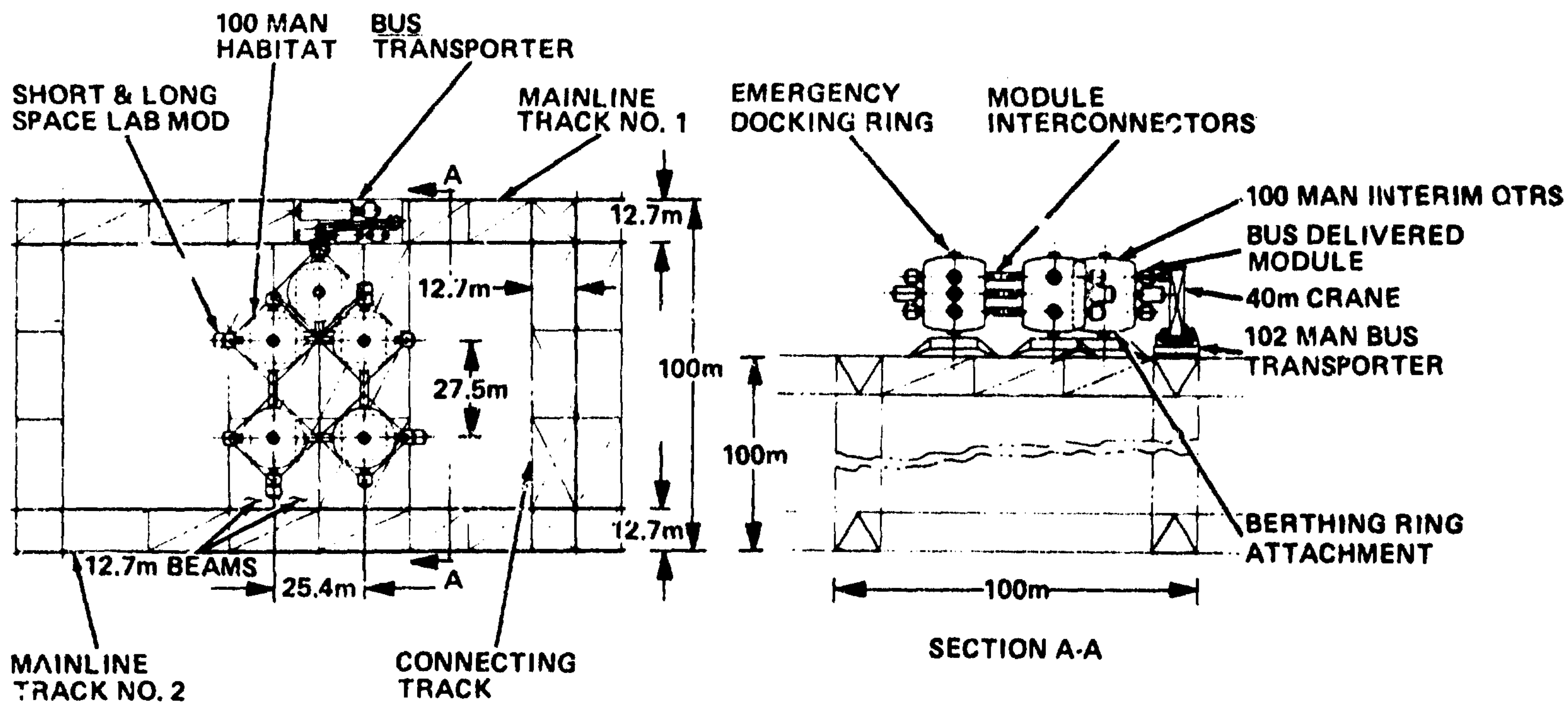
BASE HABITAT AREA – 400 PEOPLE

Four (4) habitat modules, 17.0 meters in diameter, are grouped together in a geometric pattern. Initially each module is transported to this site by the large crane on the railroad system. The bottom of each module has a large berthing ring which mates with one on the previously installed mounting platform. Guy wires (not shown) running to the Factory structure will provide stability to the installed module. The fifth module nestled between two of the habitat modules serves as an interim quarters module for 100 crew members. When all five modules are firmly installed, 12 interconnectors are installed. These connectors provide traffic flow between all the modules. Each habitat has five (5) radially located berthing ports to which the following Spacelab-type modules can be affixed:

- Short Spacelab (1) to serve as a 4-6 man EVA airlock
- Short Spacelab (1) to serve as an interface module for shirt sleeve transfer to another pressurized module such as MRWS closed cabin cherry picker & MRWS free flyer
- Long Spacelab (1) to provide for a 90 day re-supply of food for 100 people
- Short Spacelab (1) to provide re-supply of expendables
- Short Spacelab (1) to provide storage for all waste which will be returned to earth.

The interim module has three (3) radially located berthing ports to which Spacelab type modules can be affixed.

BASE HABITAT AREA — 400 PEOPLE



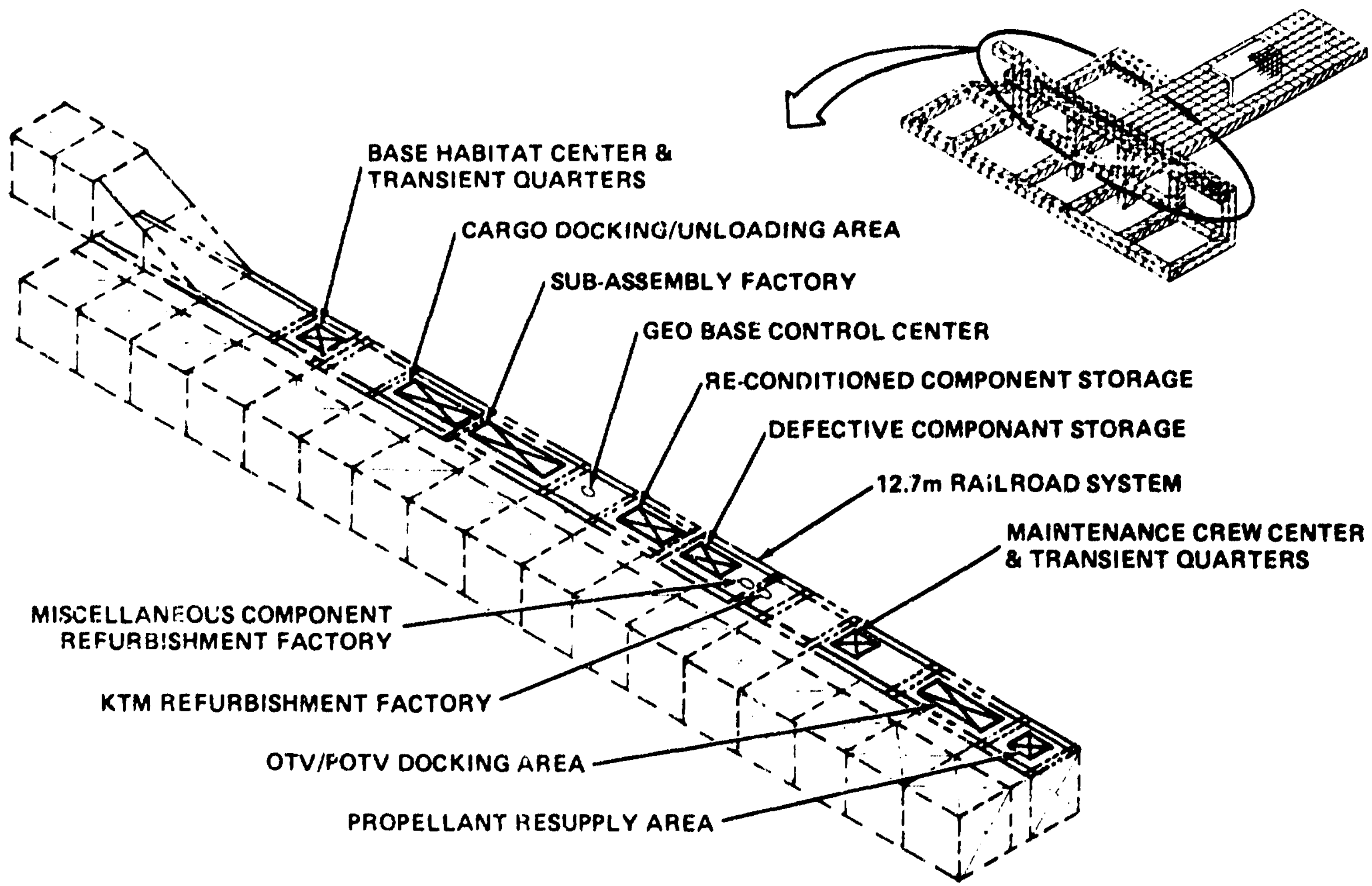
GEO BASE LEVEL "J" ARRANGEMENT

The center of activity is at the Level "J" surface. The material and men are brought to this level from the LEO base and the SPS service crew, with their materials, depart from here. In addition, numerous vertically moving transportation devices interface with supplies and personnel here for delivery to the lower levels.

Starting from the left, the following areas of activity are defined:

- Base Habitat Center & Transient Quarters – Four (4) Habitat Modules and one (1) Transient Quarters Module are grouped together here. Four hundred (400) people are quartered here and one hundred (100) transients can be accommodated
- Cargo Docking/Unloading Area – The KTM modules and Cargo Pallets are landed here and unloaded onto railroad flatcars for delivery to their next station
- Subassembly Factory – The hardware in the Cargo Pallets is delivered to this area for subassembly work prior to its movement to the lower levels for installation
- GEO Base Control Center – This module is the same size as a Habitat. A crew of sixty-five (65) control the operations of the GEO base from this area
- Reconditioned Component Storage – Those components which have been reconditioned and repaired in the KTM & Miscellaneous Component Refurbishment Factories are stored here until needed
- Defective Component Storage – Those components which have to be reconditioned and repaired are stored here. When room and scheduling permits, they are transported from here to the Refurbishment Factories.
- Miscellaneous Component Refurbishment Factory – This module has facilities within it for refurbishment of electrical, electronic and mechanical devices. Components are disassembled and assembled, as well as tested, in this area
- KTM Refurbishment Factory – All defective klystrons from the outlying SPS stations are brought into this module for refurbishment
- Maintenance Crew Quarters & Transient Quarters – Four (4) Habitat Modules and one (1) Transient Quarters Module are grouped together here. Four hundred (400) maintenance people and one hundred (100) transients are quartered here
- OTV/POTV Docking Area – Sufficient docking pads are located here for the landing of POTVs and OTVs
- Propellant Resupply Area – Quantities of propellant for refueling the OTVs are stored here.

GEO BASE LEVEL "J" ARRANGEMENT



GRUMMAN

1073-053D

SPS GEO CONSTRUCTION BASE—MIDTERM FINDINGS

- GEO CONSTRUCTION OPERATIONS STILL LOOK FEASIBLE
- BASE CREW MODULES REMAIN AS MAJOR COST/WEIGHT DRIVER
- SPS MAINTENANCE SUPPORT ALMOST DOUBLES GEO BASE CREW SIZE
- GEO CONSTRUCTION CREWS MIGHT BE REDUCED FURTHER BY CONSIDERING A HIGHLY AUTOMATED BASE
- LARGE GEO BASE WORK FORCE MAY NECESSIATE DESIGNING TO LOWER RADIATION LIMITS
- GEO BASE CONSTRUCTION ATTITUDE IMPOSES EOTV UNLOADING CONSTRAINTS

GRUMMAN

1079-064

SPS GEO CONSTRUCTION BASE—MIDTERM RECOMMENDATIONS

- NARROW SCOPE OF REMAINING CONSTRUCTION ANALYSIS
  - EMPHASIZE ENERGY CONVERSION SYSTEM & ITS MAJOR SUBSYSTEM INSTALLATIONS (SOLAR ARRAYS & POWER BUS)
  - REEXAMINE ANTENNA CONSTRUCTION CONCEPT WHEN DESIGN MATURES FURTHER
- REFINE GEO BASE SYSTEM MASS & COST DATA
  - INVESTIGATE HIGHLY AUTOMATED BASE
  - ESTABLISH CREW ROTATION/TRAINING REQMTS
  - COMPLETE HABITAT ECLS CONSUMMABLE ANALYSIS
  - DEFINE MAJOR ELEMENTS OF BASE LOGISTICS
  - UPDATE MAJOR CONSTRUCTION EQUIPMENT FUNCTIONS
  - DEFINE BASE SYSTEM ELEMENTS & INTERFACES
- DEFINE GEO BASE BUILDUP CONCEPT
- RECOMMEND AREAS FOR FURTHER EFFORT/NEAR-TERM DEVELOPMENT
- PREPARE GEO BASE OPERATIONS PLAN

GRUMMAN

1079-065

PLANNING TOPICS

The program planning analysis will be discussed under the topics indicated.

Planning Topics

- PROGRAM APPROACH
- RESEARCH PLAN STATUS
- RESEARCH COSTS AND SCHEDULING
- DEVELOPMENT ISSUES
- PROTOTYPING

SPS PHASED PROGRAM APPROACH - ACTIVITIES & DECISION CRITERIA

An overall program approach has been developed for SPS to serve as a guide to program planning. The philosophy calls for increasing program committments in measured steps, in response to successful fulfillment of decision criteria. Major resource committments are deferred until high confidence of success is established. Success is measured in terms of environmental acceptability, social, political and economic acceptability, cost confidence, and technical practicality. This overall program approach is illustrated in Figure 27. This figure shows the major activities to be conducted in each phase, the criteria to be met, and the key issues to be resolved in each area of concern. Following the research, development, and evaluation phase, the program would move into an engineering development and cost verification phase, followed by a phase of prototype construction, and finally a period of commercialization.

Our planning activity is directed to the cost achievability and technical practicality elements of the program.

The duration of the program phases is thought to be roughly five years each for the first two. The first of these would include research, technology and evaluation, and the second covers engineering development and cost verification. A demonstration phase lasting roughly ten years would follow. In a practical sense, divisions between the phases will be somewhat less distinct than indicated by the accompanying figure. It is likely that, to some degree, decisions will be made incrementally and that certain activities will not fit cleanly into one phase or another. further, some degree of overlap between the phases is possible. The amount of overlap must be selected based on a trade-off of risk versus need. Overlap of the phases would allow accomplishment of end results earlier, but would subject the program to greater expenditure before all criteria from a previous phase are met.

SPS PHASED PROGRAM APPROACH ACTIVITIES AND DECISION CRITERIA

AREA OF CONCERN • KEY ISSUES	PROGRAM PHASE						
	RESEARCH, DEVELOPMENT & EVALUATION		ENGINEERING DEVELOPMENT & COST VALIDATION		COMMERCIAL PROTOTYPE DESIGN & DEMONSTRATION		COMMERCIALIZATION
ENVIRONMENTAL ACCEPTABILITY • MICROWAVE BIOLOGICAL EFFECTS • MICROWAVE COMMUNICATION EFFECTS • POLUTION	• TEST ECOLOGICAL MICROWAVE EFFECTS • EVALUATE POLLUTION SOURCES, LEVELS & EFFECTS • TEST & ANALYZE EMI/RFI • EVALUATE OCCUPATIONAL HAZARDS • PREPARE PRELIMINARY ENVIRONMENTAL IMPACT STATEMENTS	ENVIRON-MENTAL EFFECTS UNDER-STOOD	• REVIEW & FINALIZE ENVIRONMENTAL IMPACT STATEMENTS • DEFINE ENVIRONMENTAL STANDARDS • MODIFY SYSTEM SPECIFICATIONS & DESIGNS AS REQUIRED	DRAFT ENVIRON-MENTAL IMPACT STATEMENT COMPLETE STANDARDS ADOPTED	• MONITOR & ASSESS ENVIRONMENTAL EFFECTS OF DEVELOPMENT SYSTEMS • DEVELOP DESIGN & OPERATIONAL MODIFICATIONS TO MINIMIZE ENVIRONMENTAL IMPACTS	ENVIRON-MENTAL ACCEPT-ABILITY DEMON-STRATED	• MONITOR & ENFORCE ENVIRONMENTAL STANDARDS
SOCIAL, POLITICAL & ECONOMIC ACCEPTABILITY • LAND USAGE • COMPETITIVE ECONOMICS • POWER CENTRALIZATION • INTERNATIONAL ACCEPTANCE • SOCIAL & POLITICAL INVOLVEMENT	• CONDUCT COMPARATIVE ASSESSMENTS • CONDUCT PUBLIC HEARINGS • ANALYZE EFFECTS ON U.S. & WORLD ECONOMIES & SOCIAL STRUCTURES • EVALUATE SYSTEM SITING • EVALUATE UTILITY ECONOMICS • EVALUATE MILITARY IMPLICATIONS	ISSUES DEFINED AND POTENTIAL RESOLU-TIONS IDENTI-FIED	• SELECT PROTOTYPE SITE(S) • CONDUCT INTERNATIONAL NEGOTIATIONS • FINALIZE ORBIT SLOT SELECTION & FREQUENCY ASSIGNMENT • SELECT FINANCIAL MGMT APPROACH • DEFINE REGULATORY STRUCTURE	ACCEPTABLE IMPLEMEN-TATION SPECIFICS ESTABLISHED	• IMPLEMENT PROTOTYPE SITE(S) • MONITOR & ANALYZE EFFECTS OF DEVELOPMENT PROGRAM ON U.S. & WORLD ECONOMY • IMPLEMENT TREATIES • IMPLEMENT MGMT FINANCIAL & REGULATORY ARRANGEMENTS	SOCIAL BENEFITS & ACCEPTABILITY DEMON-STRATED	• REGULATE SPS INDUSTRIES TO SOCIALLY ESTABLISHED STANDARDS
COST ACHIEVABILITY • COST PREDICTION • COST UNCERTAINTY • RISK MANAGEMENT	• CONDUCT COSTING & UNCERTAINTY ANALYSES • EVALUATE DESIGN APPROACH & TECHNOLOGY APPLICATION COST EFFECTIVENESS • CONDUCT PROGRAM COST/RISK TRADEOFF STUDIES	COST EFFECTIVE TECHNOL-OGIES IDENTIFIED	• DEVELOP & DEMONSTRATE COST CRITICAL PROCESSES AND SUBSYSTEMS • CONDUCT IN DEPTH COST ESTIMATES & UNCERTAINTY ASSESSMENTS • DEFINE RISKS & ESTABLISH RISK MANAGEMENT PLAN	COST ACCEPT-ABILITY OF DESIGNS & PROCESSES ESTABLISHED RISKS DEFINED AND CONTROL IMPLE-MENTED	• CONTROL COSTS & MANAGE RISKS • UPDATE ENERGY-ECONOMICS ASSESSMENTS	ECONOMIC COST/BENEFIT DEMON-STRATED	• CONTROL COSTS & IMPROVE ECONOMIC PERFORMANCE
TECHNICAL PRACTICALITY • LARGE SCALE POWER GENERATION • EFFICIENT POWER TRANSMISSION • SPACE TRANSPORTATION • SPACE ASSEMBLY • SYSTEM LIFE	• CONDUCT TECHNOLOGY RESEARCH & TESTS • EVALUATE TECHNOLOGY RESULTS FOR SYSTEM APPLICATION • MAINTAIN/UPDATE REFERENCE DESIGNS	KEY TECHNICAL ISSUES RESOLVED	• DEVELOP & DEMONSTRATE TECHNICALLY CRITICAL SUBSYSTEMS & PROCESSES • DEVELOP PRELIMINARY DESIGN FOR PROTOTYPE & SUPPORT SYSTEMS • COMPLETE SYSTEM DEVELOPMENT & MANAGEMENT PLAN	DESIGN APPROACHES AND PROC PROC SELEC DESIGN SPEC COMPLETE	• DESIGN, DEVELOP FAB & TEST SPS PROTOTYPE & SUPPORTING SPACE SYSTEMS (HLLV, CONSTRUCTION BASE) • MODIFY COMMERCIAL DESIGNS BASED ON PROTOTYPE RESULTS	OPERATIONAL SUITABILITY DEMONSTR-ATED	• DESIGN, BUILD & INSTALL COMMERCIAL SATELLITES • INCORPORATE & IMPLEMENT DESIGN FEATURES TO IMPROVE ECONOMIC, ENVIRONMENTAL & TECHNICAL PERFORMANCE

FIGURE 1

RESEARCH PLANNING

The system definition studies have reached the point where a reasonably comprehensive plan for SPS research can be defined.

In order to accomplish this it has been necessary to postulate an overall S S program structure including incremental decision criteria, decision objectives and research or development accomplishments. For purposes of planning it has been assumed that the first phase of such a program will be research followed by a development phase. Rather than attempting to develop an SPS, this development phase will develop prototype subsystems and processes in order to maximize cost confidence and understand the needs of risk management at minimum expense. Finally, verification of the entire system will require some sort of prototyping or pilot plant activity. Each of these phases culminates in an evaluation and decision phase. The program would not proceed unless the evaluation is favorable in terms of environmental effects, economics, technical practicality and social considerations.

Our present status is that the research plan has been detailed. This plan will be published as a seaparate interim planning document as a part of the system definition studies. Analyses of the development and prototyping phases will be conducted in the next 4 months.

Research Planning Status

- OVERALL SPS PROGRAM STRUCTURE, POSTULATED WITH INCREMENTAL CRITERIA, DECISIONS, ACCOMPLISHMENTS
  - RESEARCH, TO RESOLVE ISSUES AND SELECT TECHNICAL APPROACHES
  - DEVELOPMENT, TO DEVELOP COST CONFIDENCE AND RISK MANAGEMENT APPROACH
  - PROTOTYPING/PILOT PLANT

- RESEARCH PLAN DETAILED
  - 173 TASKS; 130 GROUND-BASED RESEARCH; 31 SYSTEMS STUDY; 10 FLIGHT RESEARCH; 2 RELATED TO IONOSPHERE HEATING

- RESEARCH PLAN ADDRESSES ONLY TECHNOLOGY RESEARCH & SYSTEMS DEFINITION

RESEARCH PLANNING PROCESS

The principal steps in developing the research plan are tabulated on the facing page.

Research Planning Process

SPS-2812

- IDENTIFY RESEARCH ISSUES & OBJECTIVES
- DEFINE RESEARCH TASKS
- REVIEW WITH JSC
- UPDATE
- DEFINE TASK INTERRELATIONSHIPS
- PERFORM NETWORK ANALYSIS
- GENERATE SCHEDULE (NO FUNDING CONSTRAINTS)
- ASSIGN RESOURCES (MANPOWER) BY SKILL
- CONDUCT COST ANALYSIS
- PERFORM COST-CONTROLLED SCHEDULING

TECHNICAL AREAS

The research plan is divided into the ten technical areas tabulated on the facing page. In addition, the research plan includes certain systems study and flight research activities.

Technical Areas

- SOLAR ARRAYS
- THERMAL ENGINES & SYSTEMS
- POWER TRANSMISSION
- STRUCTURES
- MATERIALS
- FLIGHT & SYSTEM CONTROL
- SPACE CONSTRUCTION
- SPACE TRANSPORTATION
- POWER DISTRIBUTION & PROCESSING
- SPACE ENVIRONMENT EFFECTS

SPS RESEARCH PLANNING DETAILED WORKSHEET

ıe research plan was developed through worksheets employing the fcrmat indicated. The ob..:ti es of each c. the key questions was to resolve a key issue or to select the best technology in a given area. The "implications" heading indicates the reason for the question. "Applicability" shows where this research item applies on the SPS system. The remainder of the headings summarize the task data inputs describing the research task necessary to an: /er the question. Entries of this nature were prepared for each of the 173 research tasks.

SPS Research Planning Detailed Worksheet

SUBPROGRAM	SUBJECT	KEY QUESTIONS	IMPLICATIONS	APPLICABILITY	TASKS & NETWORK NO.	DURATION (WORK DAYS)	NON-RESOURCE COST	TASKS FED & LA/26	RESOURCES
SOLAR ARRAYS	SILICON SOLAR BLANKET TECHNOLOGY								
		What processes can be used for mass production?	Energy consumption, cost, and raw material requirements.	Silicon reference SPS and EOTV	Analyze, test and evaluate cell/blanket production process.	750	$750K Matls, Equip., & STE	010101088 FS-100 011101018	1.8:4 1.7:2 4.8:1 1.9:1 3.1:2 4.8:4 1.1:1 3.2:2 1.3:1 3.4:2 4.1:1 1.5:1 3.5:2 4.2:1

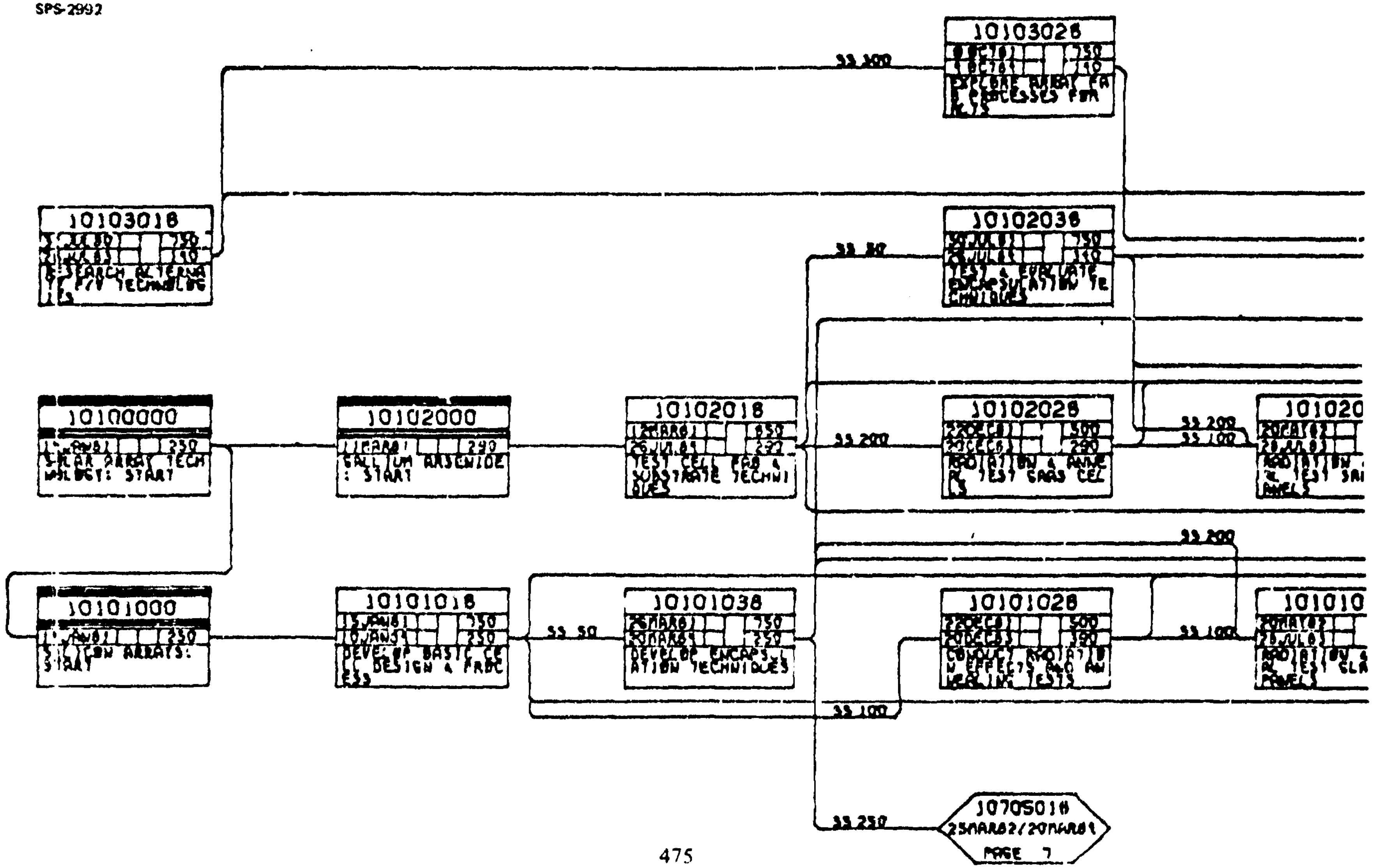
(5) TASK NUMBERING CODE: AA BB CC DD E

AA designates program phase:
01 = ground-based research;
02 = research flight tests.
BB designates technical area,
e.g., solar arrays
CC designates subject; e.g., silicon solar cells
DD designates task number
E designates priority, 0-9 with 9 highest

NETWORK EXAMPLE

The data from the research planning worksheets were input to an automated network analysis. One of the useful outputs of this analysis was a plot of the event logic network for each research area. A segment of a network is illustrated here.

Example Task Network (Solar Arrays)



SEGMENT OF SCHEDULE

Schedules as illustrated were developed for each of the technical areas.

Segment of Schedule

SPS-2967

```
                                 SOLAR POWER SATELLITE

RUN DATE 30MAY79 1540HRS          W O R K I N G    S C H E D U L E                PROJECT START 15J[illegible]

PROJECT  GBER      RESEARCH, DEVELOPMENT, & EVALUATION                              BASE COMPLETION 23JUL8[illegible]

CODE        1  SOLAR ARRAYS                         SORT   CODES  23                              PAGE   1
---------------------------------------------------------------------------------------------------------------------------
                                          MODE=0/FR     /...1980..../...1981..../...1982..../...1983..../...1984..../1985.
   ACTIVITY  D E S C R I P T I O N                      JFMAMJJASONDJFMAMJJASONDJFMAMJJASONDJFMAMJJASCNDJFMAMJJASONDJFMAMJ
--------------------------------------------------------I---------I---------I---------I---------I---------I---------I-----
                                                        I    I    I    I    I    I    I    I    I    I    I    I    I    I
SOLAR ARRAY TECHNOLOGY: START                           M
   10100000                                             I    I    I    I    I    I    I    I    I    I    I    I    I    I
SILICON ARRAYS: START                                   M
   10101000                                             I    I    I    I    I    I    I    I    I    I    I    I    I    I
DEVELOP BASIC CELL DESIGN & PROCESS                                 XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
   10101018                                             I    I    I    I    I    I    I    I    I    I    I    I    I    I
CONDUCT RADIATION EFFECTS AND ANNEALING TESTS                                   XXXXXXXXXXXXXXXXXXXXXXXXX
   10101028                                             I    I    I    I    I    I    I    I    I    I    I    I    I    I
DEVELOP ENCAPSULATION TECHNIQUES                                                XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
   10101038                                             I    I    I    I    I    I    I    I    I    I    I    I    I    I
RADIATION & ANNEAL TEST GLASSED PANELS                                                      XXXXXXXXXXXXXXX
   10101048                                             I    I    I    I    I    I    I    I    I    I    I    I    I    I
TEST & EVALUATE CELL/BLKT PROD PROCESSES                                                         XXXXXXXXXXXXXXXXXXXXXXXXX
   10101058                                             I    I    I    I    I    I    I    I    I    I    I    I    I    I
TEST & EVALUATE SAMPLE PRODUCTION PANELS
   10101068                                             I    I    I    I    I    I    I    I    I    I    I    I    I    I
GALLIUM ARSENIDE: START                                 M
   10102000                                             I    I    I    I    I    I    I    I    I    I    I    I    I    I
TEST CELL FAB & SUBSTRATE TECHNIQUES                                XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
   10102018                                             I    I    I    I    I    I    I    I    I    I    I    I    I    I
RADIATION & ANNEAL TEST GAAS CELLS                                              XXXXXXXXXXXXXXXXXXXXXXXXX
   10102028                                             I    I    I    I    I    I    I    I    I    I    I    I    I    I
TEST & EVALUATE ENCAPSULATION TECHNIQUES                                        XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
   10102038                                             I    I    I    I    I    I    I    I    I    I    I    I    I    I
RADIATION & ANNEAL TEST SAMPLE PANELS                                                       XXXXXXXXXXXXXXX
   10102048                                             I    I    I    I    I    I    I    I    I    I    I    I    I    I
TEST & EVALUATE CELL/BLKT PROD PROCESSES                                                         XXXXXXXXXXXXXXXXXXXXXXXXX
   10102058                                             I    I    I    I    I    I    I    I    I    I    I    I    I    I
TEST & EVALUATE SAMPLE PRODUCTION PANELS
   10102068                                             I    I    I    I    I    I    I    I    I    I    I    I    I    I
TEST & DEMONSTRATE GALLIUM RECOVERY                                                         XXXXXXXXXXXXXXXXXXXX
   10102078                                             I    I    I    I    I    I    I    I    I    I    I    I    I    I
```

SEGMENT OF RESOURCES DATA

Costs for the research program were developed by estimating headcount and durations by skill for each of the tasks. Shown on the facing page is a segment of resources data. Integer resources such as 1.00 and 3.00 are summaries of the specific skills underneath each of these integers i.e., 1.00 sums the skills 1.1 through 1.9. These summary resources were used in presenting resource requirements data and in conducting rescurce constrained scheduling.

Segment of Resources Data

SORT NODE PAGE 2

ACTIVITY NODE=O/FE	RESOURCE	DESCRIPTION	DAILY USAGE	TOTAL USAGE		DUR	START	FINISH
	10.30	LARGE COMB ENVIR CHAMBER	0.5	150.0	TESTDAYS			
10101058		TEST & EVALUATE CELL/BLKT PROD PROCESSES				750	4JUN81	29MAY84
	1.00	TECHNOLOGY ENGINEERING	10.0	7500.0	MAN DAYS			
	1.10	MECHANICAL/STRUCT ENGINEERING	1.0	750.0	MAN DAYS			
	1.30	ELECTRIC POWER ENGINEERING	1.0	750.0	MAN DAYS			
	1.50	CHEMICAL/PROCESS ENGINEERING	1.0	750.0	MAN DAYS			
	1.70	MATH & SOFTWARE ENGINEERING	2.0	1500.0	MAN DAYS			
	1.80	INDUST DESIGN & PLANT ENGR	4.0	3000.0	MAN DAYS			
	1.90	CIVIL & FACILITIES ENGINEERING	1.0	750.0	MAN DAYS			
	3.00	TECHNICAL SUPPORT	8.0	6000.0	MAN DAYS			
	3.10	ENGR AIDES, DRAFTING	2.0	1500.0	MAN DAYS			
	3.20	CLERICAL, GRAPHICS	2.0	1500.0	MAN DAYS			
	3.40	MECHANICAL LAB TECHS	2.0	1500.0	MAN DAYS			
	3.50	ELECTRICAL LAB TECHS	2.0	1500.0	MAN DAYS			
	4.00	MANUFACTURING	7.0	5250.0	MAN DAYS			
	4.10	MECH/STRUCT DEV SHOP	1.0	750.0	MAN DAYS			
	4.20	ELEC/ELECTRONIC DEV SHOP	1.0	750.0	MAN DAYS			
	4.50	SPECIALTY SHOP	1.0	750.0	MAN DAYS			
	4.80	PROCESS PLANT SHOP	4.0	3000.0	MAN DAYS			
10101068		TEST & EVALUATE SAMPLE PRODUCTION PANELS				150	11JAN84	9AUG84
	1.00	TECHNOLOGY ENGINEERING	1.0	150.0	MAN DAYS			
	1.30	ELECTRIC POWER ENGINEERING	1.0	150.0	MAN DAYS			
	3.00	TECHNICAL SUPPORT	4.0	600.0	MAN DAYS			
	3.10	ENGR AIDES, DRAFTING	1.0	150.0	MAN DAYS			
	3.20	CLERICAL, GRAPHICS	1.0	150.0	MAN DAYS			
	3.50	ELECTRICAL LAB TECHS	2.0	300.0	MAN DAYS			
10102018		TEST CELL FAB & SUBSTRATE TECHNIQUES				850	15JAN80	1JUN83
	1.00	TECHNOLOGY ENGINEERING	6.0	5100.0	MAN DAYS			
	1.30	ELECTRIC POWER ENGINEERING	3.0	2550.0	MAN DAYS			
	1.60	PHYSICS TECHNOLOGY	3.0	2550.0	MAN DAYS			
	3.00	TECHNICAL SUPPORT	6.0	5100.0	MAN DAYS			
	3.20	CLERICAL, GRAPHICS	3.0	2550.0	MAN DAYS			
	3.50	ELECTRICAL LAB TECHS	3.0	2550.0	MAN DAYS			
	4.00	MANUFACTURING	6.0	5100.0	MAN DAYS			
	4.20	ELEC/ELECTRONIC DEV SHOP	6.0	5100.0	MAN DAYS			
10102028		RADIATION & ANNEAL TEST GAAS CELLS				500	240CT80	210CT82
	1.00	TECHNOLOGY ENGINEERING	4.0	2000.0	MAN DAYS			
	1.30	ELECTRIC POWER ENGINEERING	2.0	1000.0	MAN DAYS			
	1.60	PHYSICS TECHNOLOGY	2.0	1000.0	MAN DAYS			

COST IS $8.3 MILLION

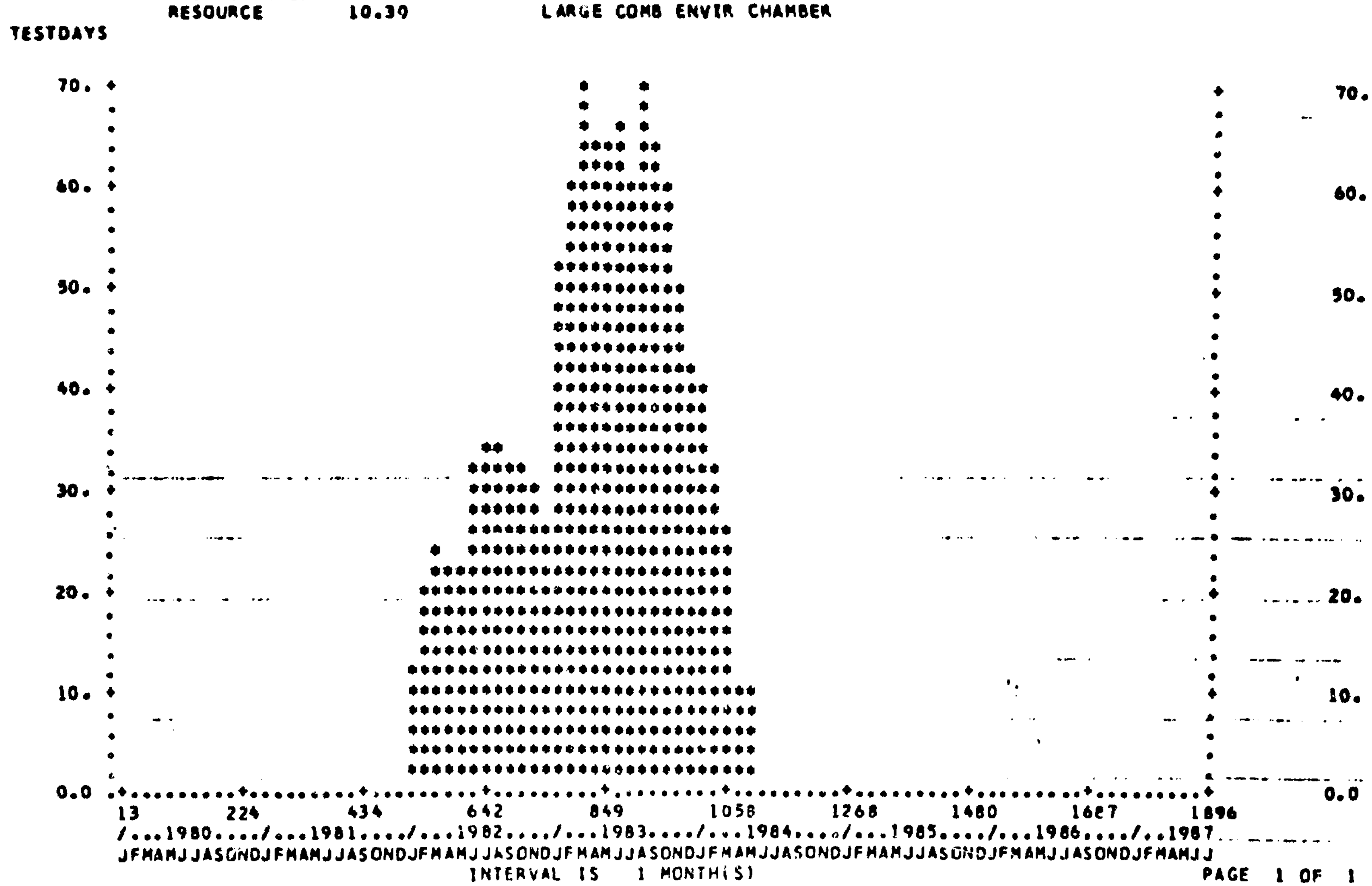
EXAMPLE RESOURCES RESULTS FACILITIES

The facing page shows requirements for one of the major facilities considered, a large combined-environment chamber. The peak requirement for 70 test days per month would indicate a need for approximately 3 such facilities for the ground-based program.

Example Resources Results Facilities

SPS-2961

PROJECT GBER TOTAL CONSUMPTION IS 1150. TESTDAYS
RESOURCE 10.39 LARGE COMB ENVIR CHAMBER



EXAMPLE RESOURCES RESULTS MANPOWER

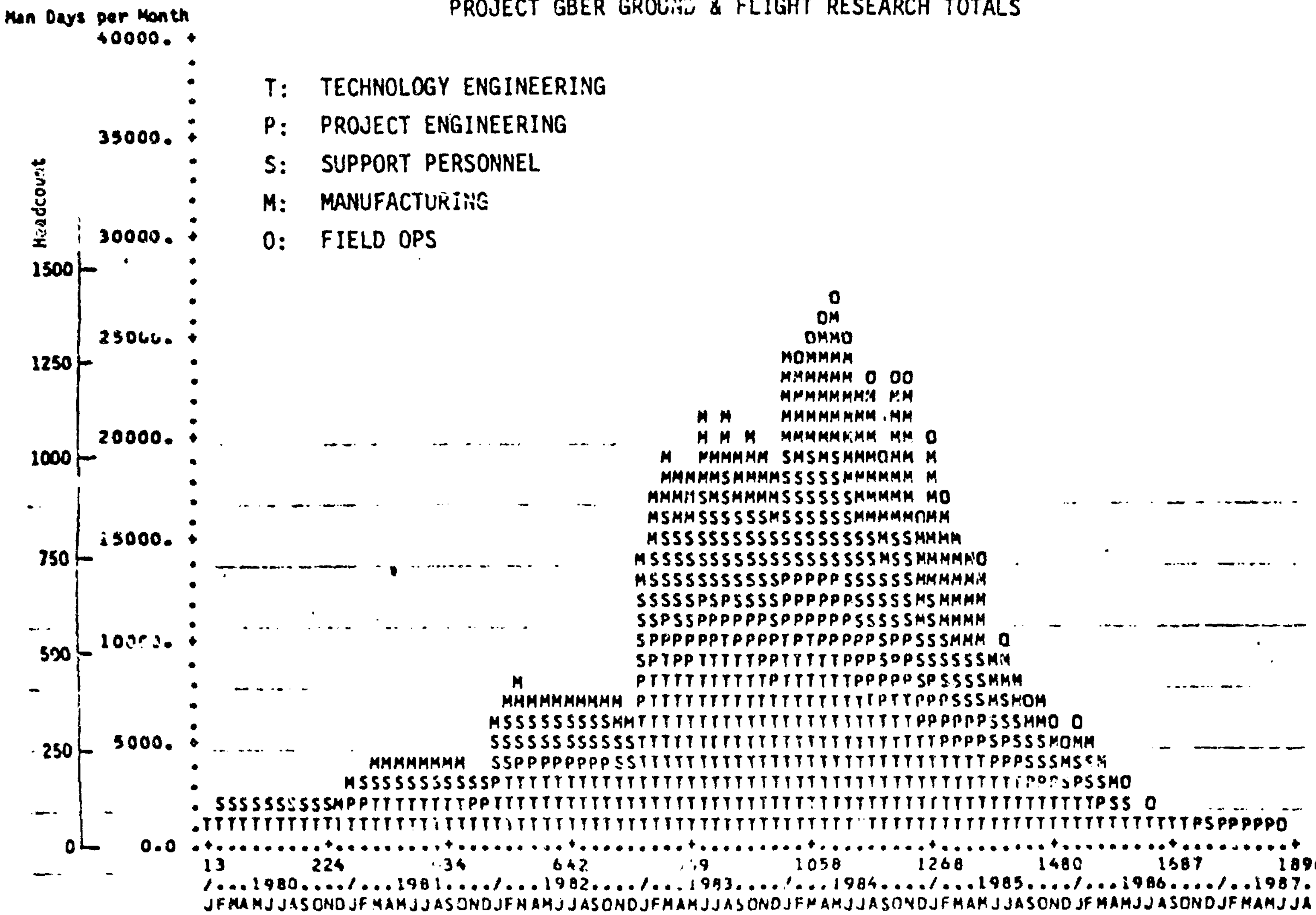
Shown on the facing page is the total manpower requirement for the research program including the ground and flight research phases. The effect of resource-constrained scheduling in the first 3 years is clearly discernable.

Example Resources Results (Manpower)

BOEING

SPS-2959

PROJECT GBER GROUND & FLIGHT RESEARCH TOTALS



ORIGINAL PAGE IS OF POOR QUALITY

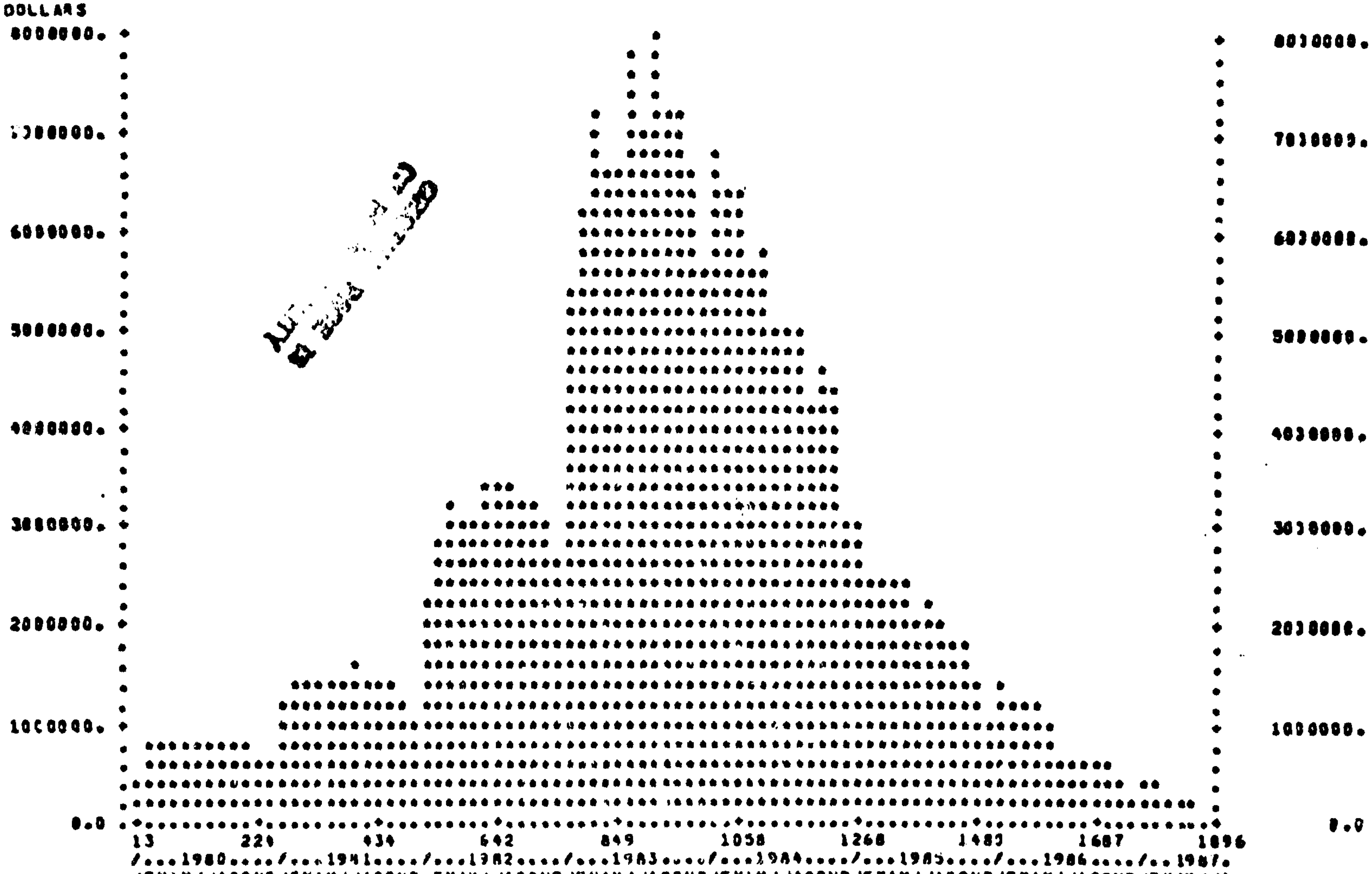
GROUND-BASED RESEARCH NOMINAL COSTS

The ground-based portion of the research program was estimated to cost a total of 240 million 1979 dollars. The scales to the left and right are in dollars per month and should be multiplied by 12 to give dollars per year.

Ground-Based Research: Nominal Costs

SPS-2964

PROJECT GBER CODE 1 GROUND-BASED RESEARCH .... TOTAL CONSUMPTION IS 239646720.



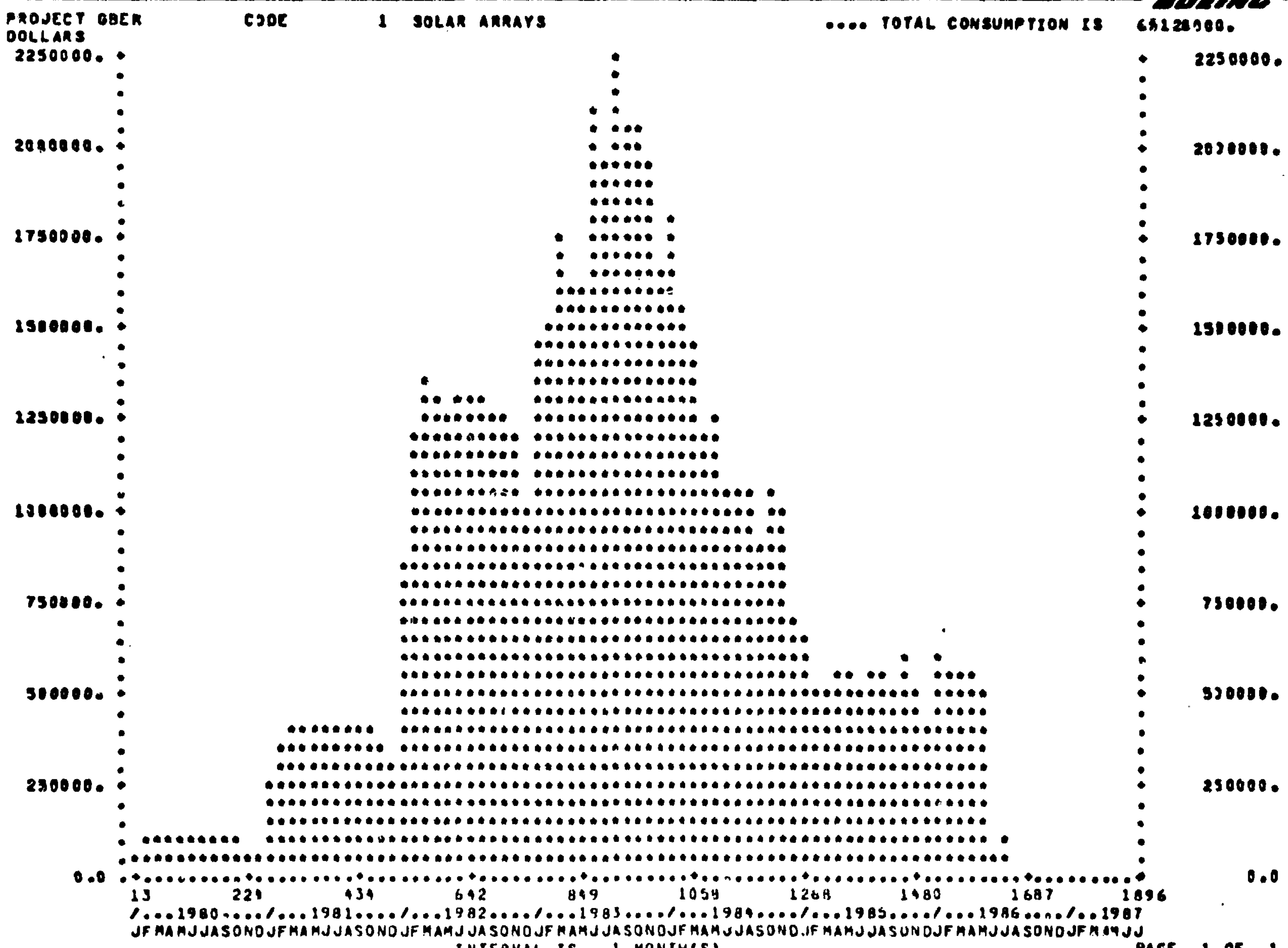
INTERVAL IS 1 MONTH(S) PAGE 1 OF 1

SOLAR ARRAYS NOMINAL COST

Cost spreads were developed for each of the technical areas. Solar array technology development was one of the more costly areas with a total of 65 million dollars.

Solar Arrays: Nominal Costs

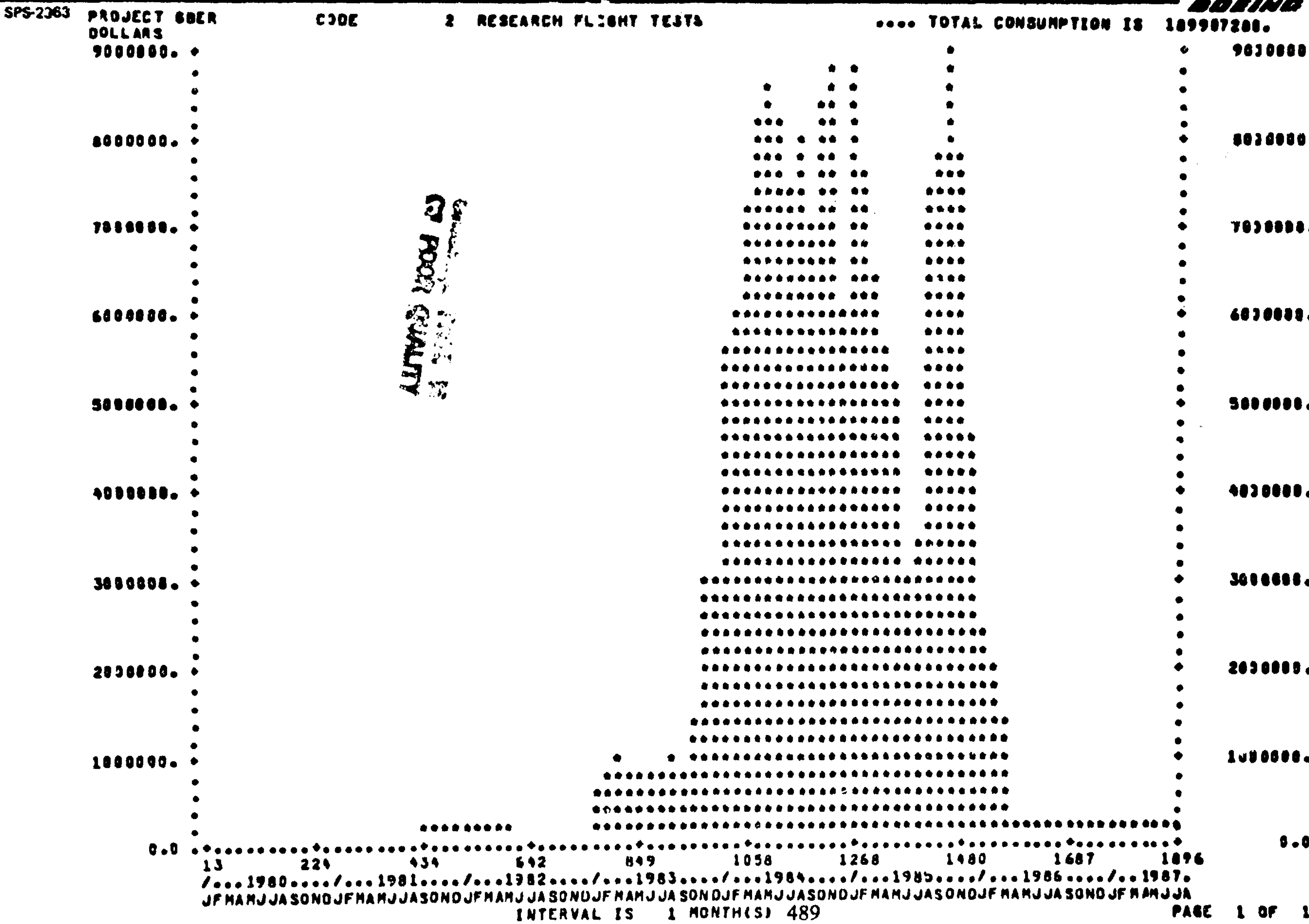
SPS-2962



FLIGHT RESEARCH NOMINAL COST

Certain of the elements of the research program required flight tests to acquire the necessary data. The total costs for flight program were roughly 190 million 1979 dollars.

Flight Research: Nominal Costs



RESEARCH FLIGHT TESTS

These three subjects were judged to require flight tests in order to accomplish the research objectives, as tabulated on the facing page.

Research Flight Tests

- MICROWAVE POWER TRANSMISSION

  LARGE APERTURE PHASED ARRAY TECHNOLOGY SATELLITE

- SPACE CONSTRUCTION

  BEAM BUILDER
  SOLAR ARRAY DEPLOYMENT

- SPACE PLASMA EFFECTS

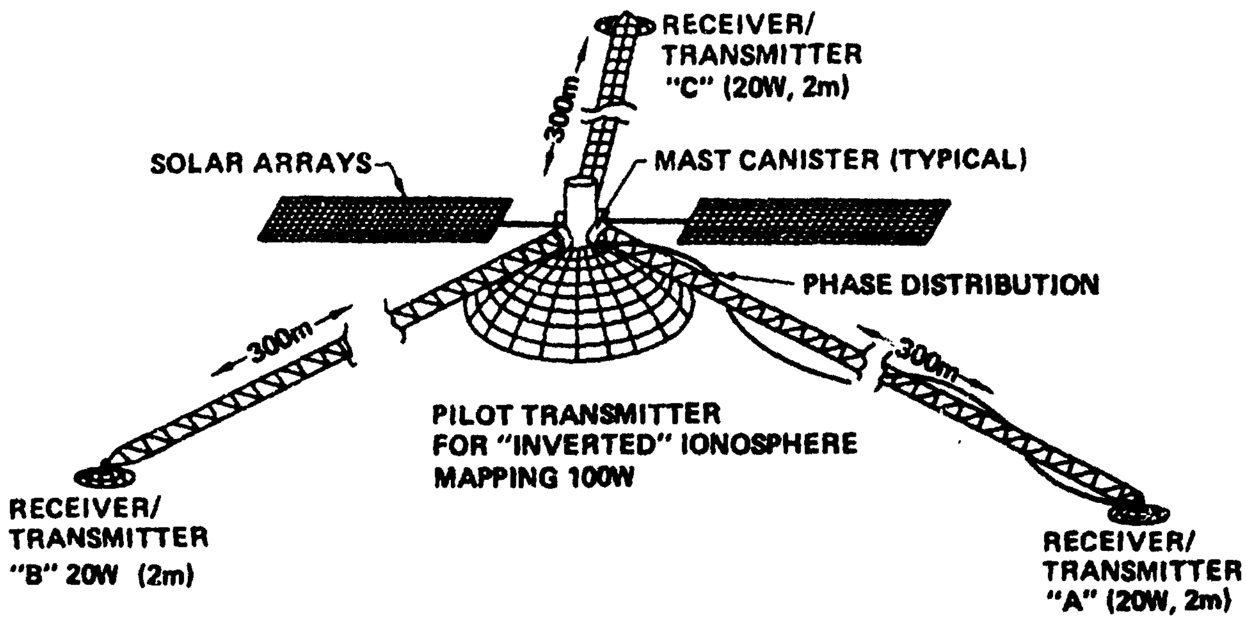
  PLASMA COLLECTION
  ELECTRIC PROPULSION THRUSTER PLASMAS
  HIGH VOLTAGE BREAKDOWN

LARGE APERTURE PHASED ARRAY TECHNOLOGY SATELLITE

The objective of this satellite experiment is to confirm the adequacy of phase control system technology for SPS application. Preliminary estimates have indicated that the satellite illustrated can be configured for shuttle/IUS launch and can be launched to geosynchronous orbit in time to support the research program.

SPS-2930

Large Aperture Phased Array Technology Satellite



RESEARCH OBJECTIVES

- EVALUATE RETRODIRECTIVE PHASE CONTROL ERROR INTRODUCED BY IONOSPHERE & RESULTING BEAM STABILITY
- ACT AS PILOT FOR IONOSPHERE MAPPING

TIMING

- ON CRITICAL PATH
- LAUNCH IN 4TH QTR 1985

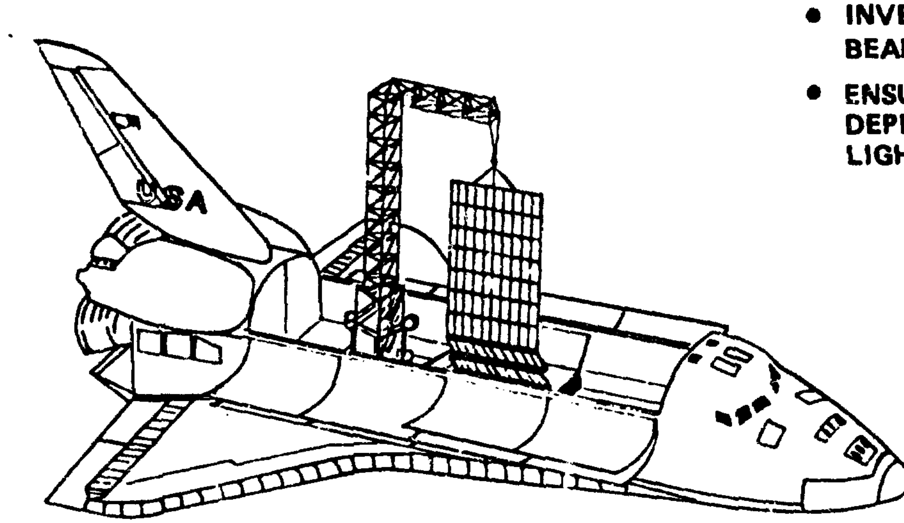
BEAM BUILDER AND SOLAR ARRAY DEPLOYMENT SORTIE

The research objectives for this shuttle sortie are indicated. In addition to confirming the successful operation of beam builder technology it is important to ensure that zero-G deployment mechanics for solar arrays in the SPS class are adequately understood, to confirm the adequacy of solar array design and packaging and deployment technology.

Beam Builder & Solar Array Deployment Sortie

RESEARCH OBJECTIVES

- EXPLORE ZERO-G DYNAMICS ON FABRICATION DEPLOYMENT
- INVESTIGATE OUTGASSING FROM BEAM FAB IN SPACE ENVIRONMENT
- ENSURE UNDERSTANDING OF ZERO-G DEPLOYMENT MECHANICS FOR SPS LIGHTWEIGHT ARRAYS



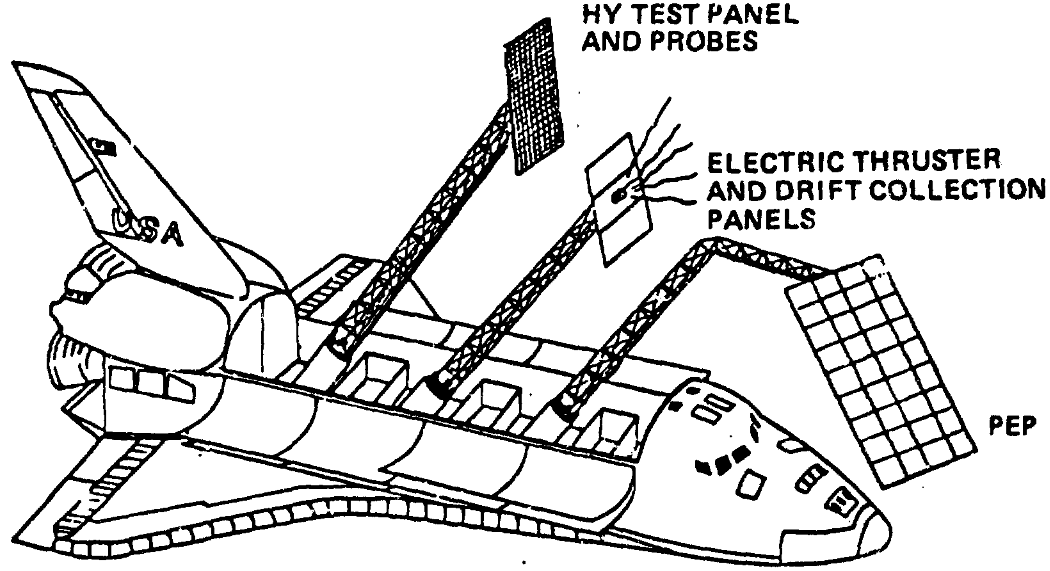
TIMING 1984-1985

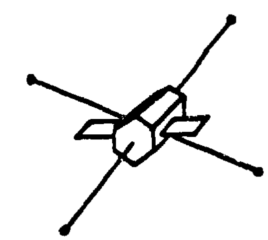
PLASMA EFFECTS SORTIE

A preliminary experimental investigation of plasma effects can be conducted in low earth orbit even though the environment there is significantly different than that at GEO. Further, the effects being investigated are important to the operation of electric orbit transfer vehicles in low earth orbit.

Plasma Effects Sorte

SPS-2928





RESEARCH OBJECTIVES

- BREAKDOWN, ARC-THRU, & PLASMA CURRENTS FOR HV SOLAR ARRAYS IN LEO
- HV ARRAY-THRUSTER INTERACTIONS
- THRUSTER PLASMA EFFECTS ON IONOSPHERE & MAGNETOSPHERE

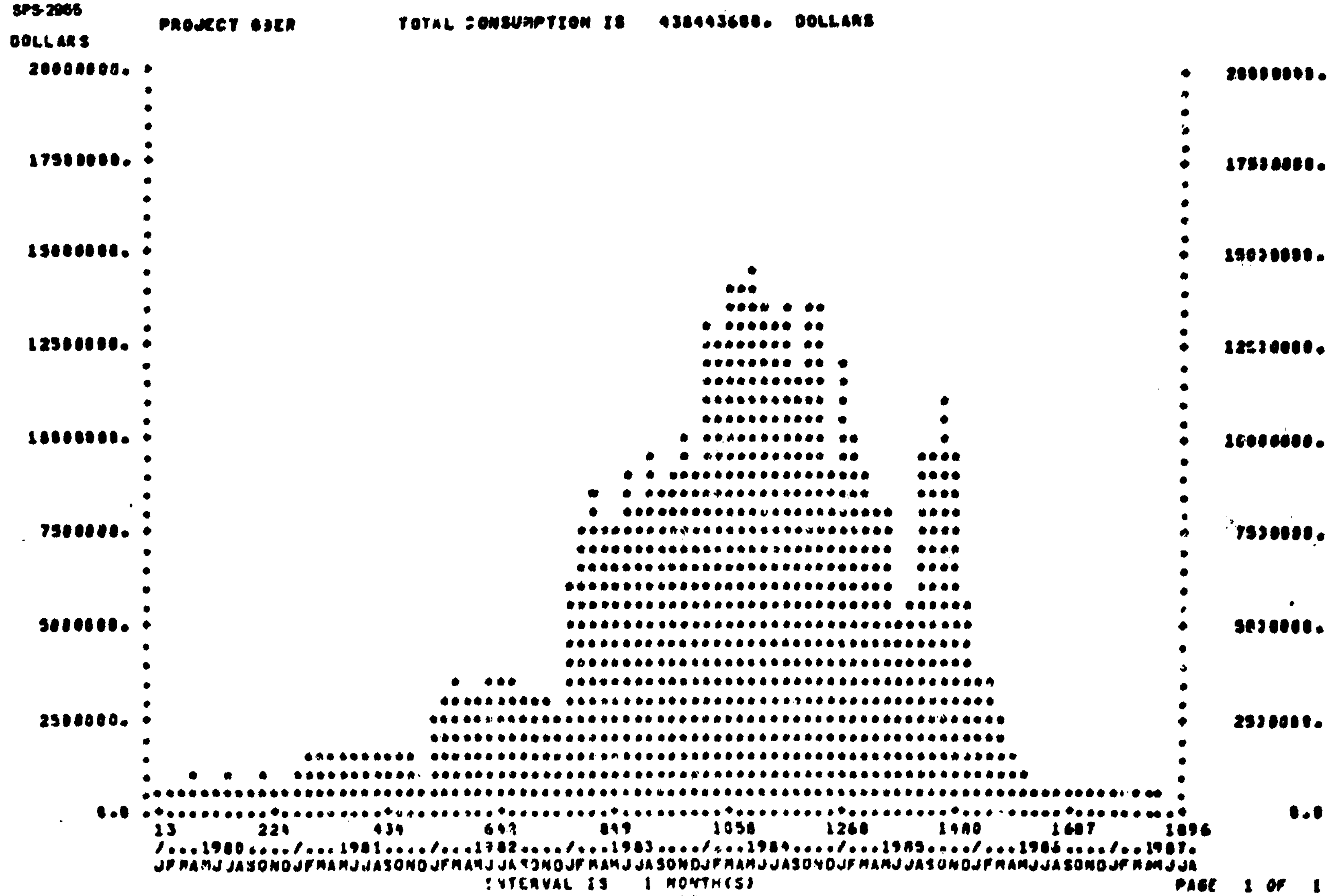
TIMING 1984-1985

TOTAL RESEARCH PROGRAM NOMINAL COSTS

The nominal (resource-constrained schedule) total program costs are exhibited here, showing completion in 1987 and a total cost over the period slightly less than 440 million dollars.

Total Research Program: Nominal Costs

SPS-2966

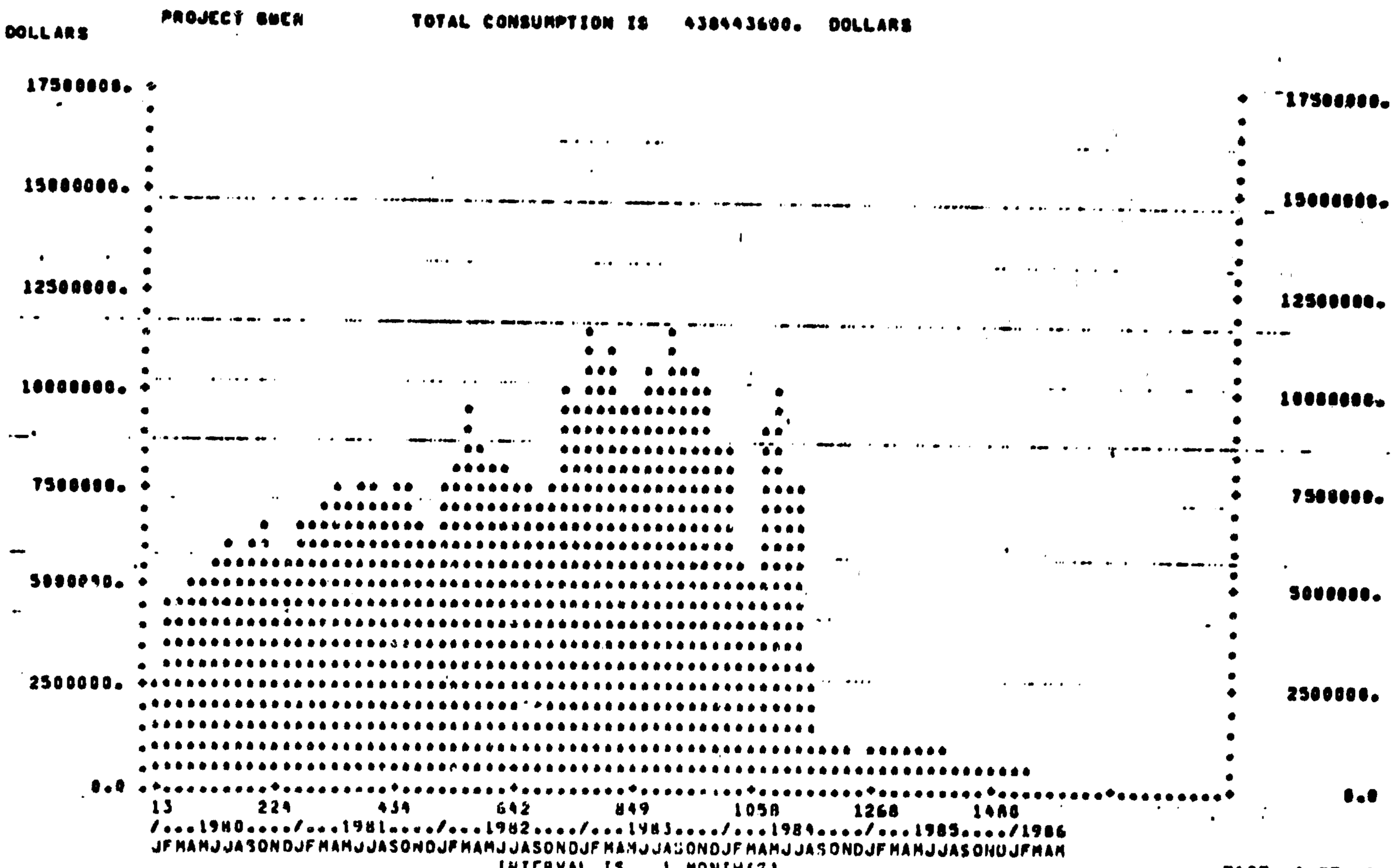


EARLY-START SCHEDULE COSTS

The early-start schedule begins each task as early as possible under the constraint of the network interrelationships; all tasks are finished as early as possible. This schedule shows the maximum funding that could be utilized early in the program. The cost scales are in dollars per month. The research program could employ as much as 60 million dollars in the first year.

"Early Start" Schedule Costs

SPS-2968

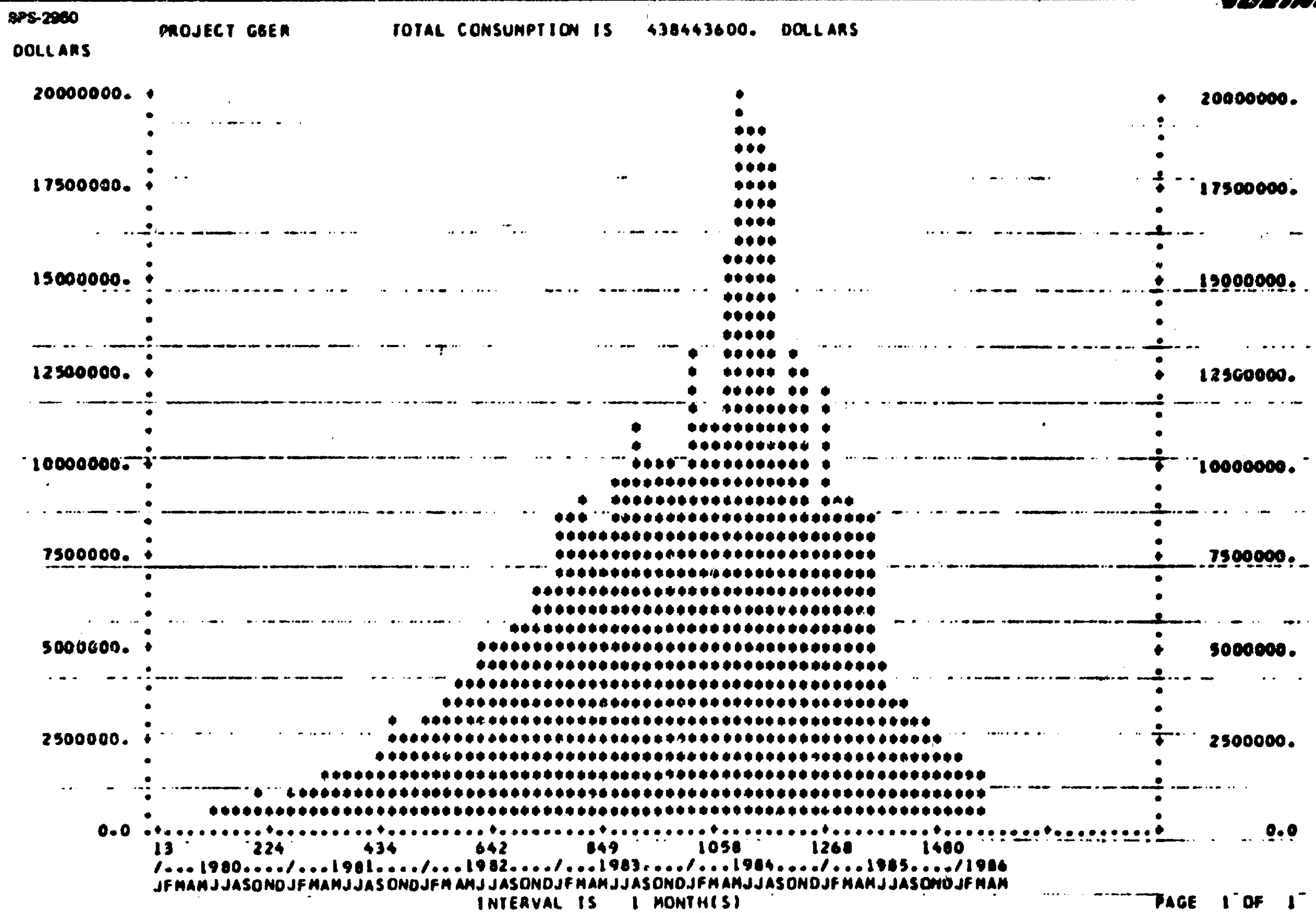


LATE START SCHEDULE COSTS

This schedule finishes at the same time as the early start schedule but defers initiation of each task to as late as possible. This schedule shows the lowest early-year funding that can be accommodated with completion of all tasks at the time the critical path sequence of tasks is completed.

Both the early start and late start schedules complete the research program at the eariliest possible date, about April 1986.

"Late Start" Schedule Costs

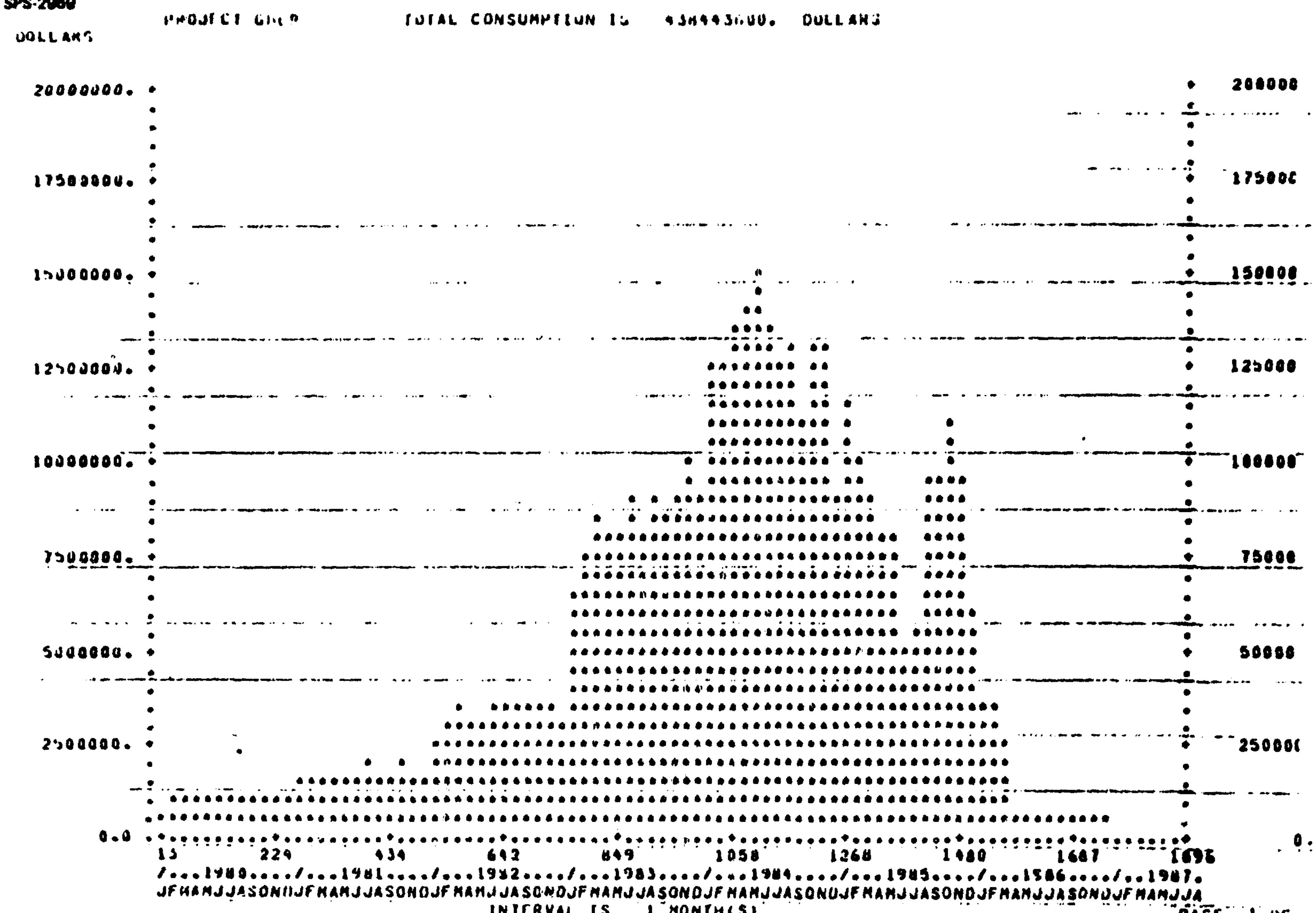


ALTERNATE CONSTRAINED SCHEDULE COSTS

An additional constrained schedule was constructed to examine sensitivity of scheduling to early year funding. This schedule allowed slightly more funding than the previous constrained schedule and finishes in late 1986 rather than mid-1987.

Alternate Constrained Schedule Costs

SPS-2000

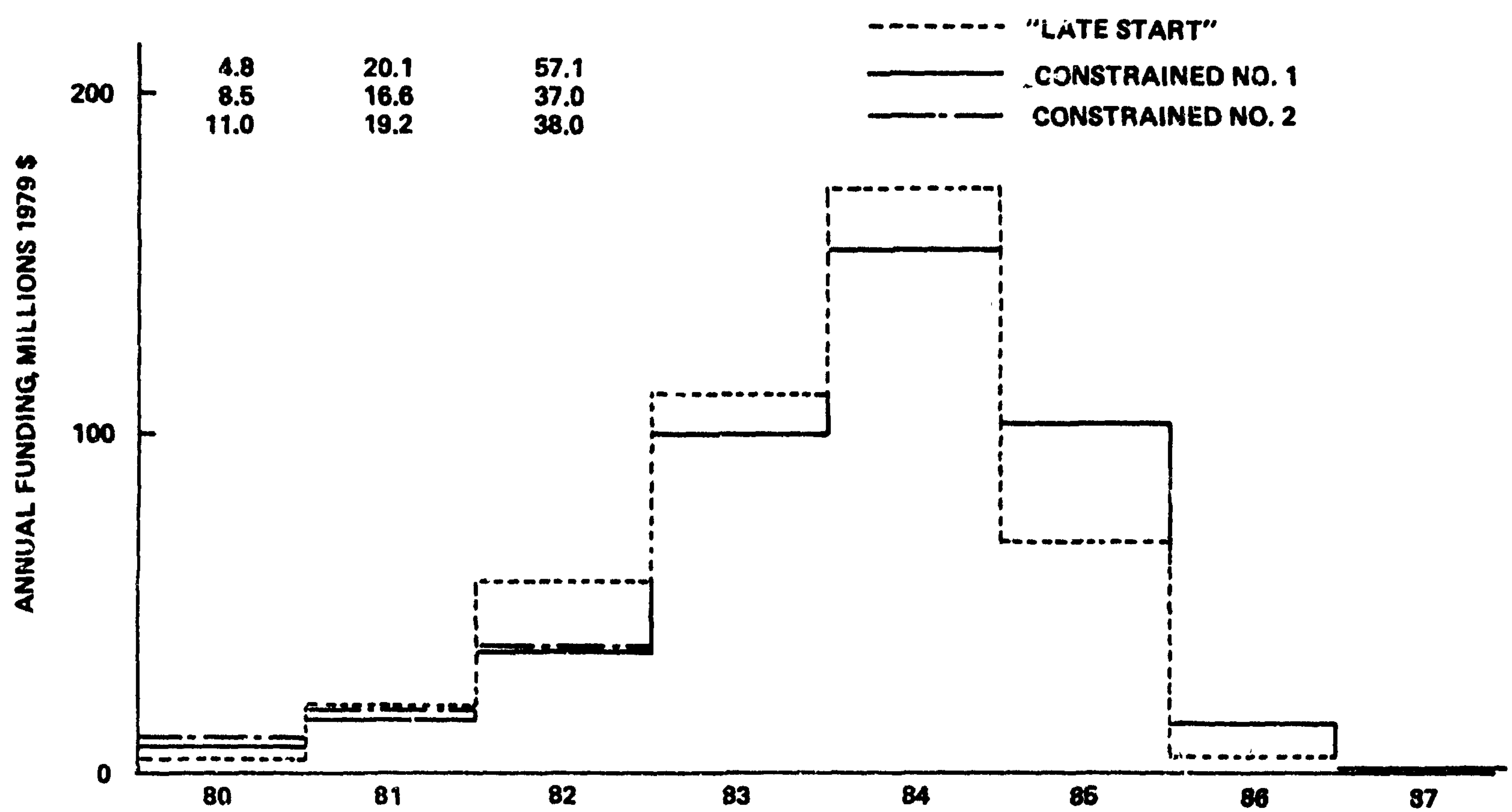


THREE FUNDING OPTIONS FOR RESEARCH PHASE

The two constrained schedules are compared here to the late-start schedule. Annual costs are also tabulated for the first three years in the upper left portion of the chart. The constrained No. 2 schedule, at slightly higher funding in the first two years, allows finishing about six months earlier than constrained No. 1. The late start schedule finishes about nine months earlier than constrained No. 2 because of the substantially higher funding allowed in the third year. Increased funding in the third year allows initiation of research flight projects. In the constrained schedules these are not initiated until 1983.

Three Funding Options For Research Phase

SPS-2919

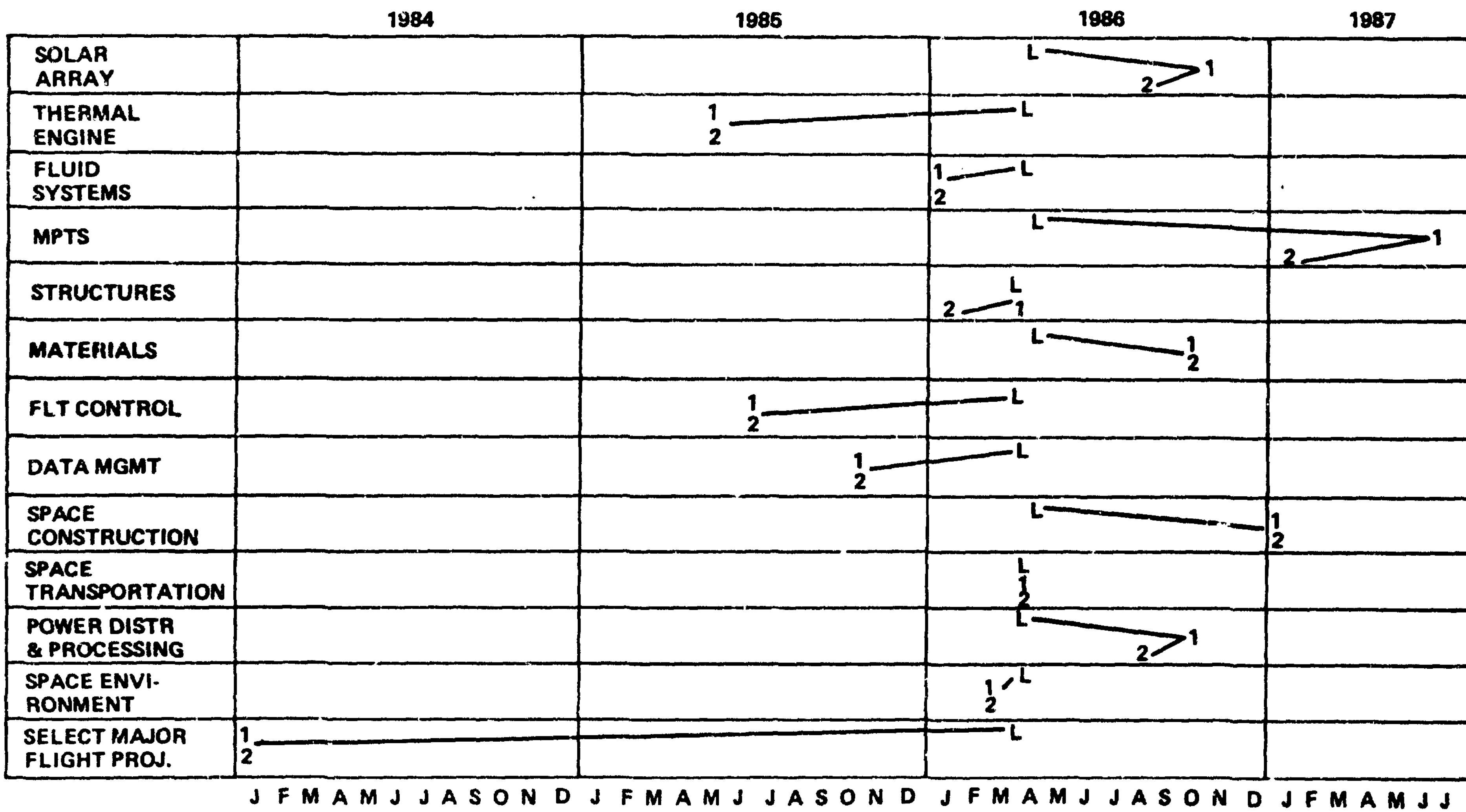


TECHNOLOGY DECISION SCHEDULE COMPARISON

The research program in each technology area culminates with a selection of the preferred technologies to carry into the development phase. This tabulation compares the date at which these technology decisions are reached for the late start schedule and for the No. 1 and No. 2 resource-constrained schedules.

Technology Decision Schedule Comparison

SPS-2920



DEVELOPMENT QUESTIONS

If the research program reaches a successful conclusion, and a continuation of the SPS program beyond the research phase is elected, the developmental phase will be aimed at selecting design approaches and production processes, developing specifications for SPS systems and subsystems, and demonstrating attainability of costs. The next ten charts provide a preliminary tabulation of questions appropriate to these objectives.

Development Questions

SOLAR ARRAYS

- WHAT ARRAY COST CAN BE ACHIEVED BY THE PROCESSES SELECTED FOR CELL/ARRAY PRODUCTION AND ASSEMBLY? WHAT QUALITY AND PERFORMANCE?
- WHAT ARE THE BEST WAYS TO PACKAGE AND DEPLOY? WHAT PRODUCTIVITY (m^2/HOUR) IS ACHIEVED AND HOW MUCH PROBLEM IS THERE WITH DAMAGE?
- WILL THE HIGH-VOLTAGE ARRAYS PERFORM RELIABLY AT GEO? WHAT VOLTAGE CAN WE GET AWAY WITH; WHAT LOSSES?
- WHAT DEGRADATION AND ANNEALING (?) EFFECTS ARE ACTUALLY EXPERIENCED?
- WHAT ARE THE RESULTING SOLAR ARRAY DESIGN CRITERIA AND PERFORMANCE DATA?

Development Questions - Con't

THERMAL SYSTEMS

- WHAT DESIGN CRITERIA AND PERFORMANCE DATA SHOULD BE USED FOR SPS THERMAL SYSTEMS?

  – HEAT REJECTION
  – REFLECTIVITY
  – FLUID CONTAINMENT
  – SUITABILITY FOR IN-SPACE FABRICATIONS AND REPAIR
  – DEGRADATION

NOTE THIS LIST ASSUMES THE NOMINAL PROGRAM, I.E., THAT THERMAL ENGINE ENERGY CONVERSION IS NOT CARRIED INTO THIS PHASE.

Development Questions - Con't

SPS-2943

MICROWAVE/LASER POWER TRANSMISSION

- WHAT DESIGN CRITERIA, PERFORMANCE, AND LIFE ARE APPLICABLE TO MICROWAVE POWER AMPLIFIERS AND LASERS OPERATING AT GEO?
- IS LABORATORY PHASE CONTROL EQUIPMENT PERFORMANCE REPRODUCIBLE WITH PROTOTYPE HARDWARE IN SPACE? WHAT DESIGN AND PERFORMANCE CRITERIA FOLLOW?
- WHAT WILL THE MICROWAVE AND LASER EQUIPMENT COST IN PRODUCTION? WHAT IS THE MOST ECONOMICAL TRADEOFF AMONG QC, QA, FAILURE RATES, AND PERFORMANCE?
- WHAT SPECIFICATIONS, PROCESSES, AND PROCEDURES SHOULD BE USED?

Development Questions - Con't

SPS-2944

BOEING

STRUCTURES

- HOW WELL DO THE ANALYTICAL PREDICTIONS, E.G., OF FINITE-ELEMENT MODELS, PREDICT THE ACTUAL DYNAMICS OF LARGE SPACE STRUCTURES? WHAT DYNAMICS UNCERTAINTIES SHOULD BE USED IN CONTROL SYSTEMS DESIGN CRITERIA?
- WHAT WILL THE STRUCTURAL ELEMENTS COST IN PRODUCTION? WHAT IS THE MOST ECONOMICAL TRADEOFF AMONG QC, QA, ALLOWABLES, AND STRUCTURAL REDUNDANCY?

MATERIALS

- WHAT DOES EXPOSURE TO THE ACTUAL ENVIRONMENTS INDICATE AS TO LIFETIMES AND DEGRADATION OF CRITICAL MATERIALS? WHAT PROTECTIVE MEANS, MATERIALS SELECTION, DESIGN CRITERIA AND ALLOWABLES SHOULD BE APPLIED?
- WHAT ARE THE MOST ECONOMICAL MATERIALS PRODUCTION PROCESSES?

Development Questions - Con't

SPS-2945

BOEING

FLIGHT CONTROL AND DATA MANAGEMENT

- DO LARGE STRUCTURES AND THEIR CONTROL SYSTEMS BEHAVE ACCORDING TO MODEL PREDICTIONS? WHAT DESIGN CRITERIA, E.G., GAIN AND PHASE MARGINS, SHOULD BE USED?
- ARE THERE ANY UNEXPECTED THRUSTER/PLASMA/MAGNETIC INTERACTIONS THAT INFLUENCE CONTROL SYSTEM DESIGN AND OPERATION?
- WHAT ARE THE SOFTWARE AND HARDWARE DESIGN CRITERIA FOR DATA MANAGEMENT? WHAT WILL THIS SYSTEM COST IN PRODUCTION? WHAT IS THE MOST ECONOMIC TRADEOFF AMONT QC, QA, REDUNDANCY, SOFTWARE/HARDWARE SELF-CORRECTION, AND MAINTENANCE?

Development Questions - Con't

SPACE CONSTRUCTION

- WHAT CREW PRODUCTIVITY IS EXPERIENCED UNDER ACTUAL CONSTRUCTION OPERATIONS?
- WHAT EQUIPMENT PRODUCTIVITY IS EXPERIENCED?
- WHAT CONSTRUCTION PROBLEMS COULD BE AVOIDED BY BETTER SPS OR EQUIPMENT DESIGN?
- WHAT CONSTRUCTION SYSTEM AND SPS DESIGN CRITERIA SHOULD BE EMPLOYED?
- WHAT CONSTRUCTION COSTS ARE SUPPORTED BY ACTUAL EXPERIENCE?

Development Questions - Continued

SPACE TRANSPORTATION

- WHAT DOES SHUTTLE/OTV EXPERIENCE INDICATE AS TO PROJECTED SPS SPACE TRANSPORTATION COSTS?
- ARE THERE ANY OPERATING PROBLEMS WITH CLUSTERS OF LARGE ELECTRIC THRUSTERS? CAN PLASMA DRIFT CURRENTS BE PREDICTED?
- WHAT BOOSTER ENGINE COSTS ARE INDICATED BY DEVELOPMENT ACTIVITIES?
- WHAT CREW PROVISIONS AND CABIN DESIGNS ARE APPROPRIATE TO CREW TRANSPORTATION?

Development Questions - Continued

SPS-2933

BOEING

POWER DISTRIBUTION AND PROCESSING

- WHAT EFFICIENCY AND MASS CHARACTERISTICS ARE ACHIEVED BY POWER PROCESSORS? WHAT WILL THEY COST IN PRODUCTION? WHAT DESIGN CRITERIA ARE APPROPRIATE TO THESE FIGURES AND TO ADEQUATE LIFE?
- WHAT PERFORMANCE CAN BE ACHIEVED BY CIRCUIT BREAKERS/INTERRUPTERS? HOW DOES PERFORMANCE TRADE WITH MASS AND COST?
- HOW DO SELECTED CABLE INSULATION MATERIALS STAND UP IN THE SPACE ENVIRONMENT?
- WHAT PLASMA AND BREAKDOWN DESIGN CRITERIA APPLY, IN THE LEO AND GEO ENVIRONMENTS, TO CONDUCTOR, INSULATOR, AND STANDOFF DESIGN?

Development Questions - Continued

SPACE ENVIRONMENT EFFECTS

- HOW DO ELECTRIC THRUSTER PLASMAS INTERACT WITH THE MAGNETOSPHERE? ARE RESEARCH RESULTS AND MODELS CONFIRMED?
- HOW DO SOLAR ARRAYS DEGRADE DURING ORBIT TRANSFER? WHAT FLUENCES ARE EXPERIENCED? ARE RESEARCH RESULTS AND MODELS CONFIRMED?
- HOW DO SHUTTLE/OTV BURNS AFFECT THE UPPER ATMOSPHERE AND IONOSPHERE? ARE RESEARCH RESULTS AND MODELS CONFIRMED?
- WHAT SYSTEMS CHOICES AND DESIGN CRITERIA FOLLOW FROM THESE RESULTS?

Development Questions, Continued

SPS-2935

BOEING

SPS SYSTEMS ENGINEERING

- WHAT IS THE MOST ECONOMIC SET OF SPS SYSTEMS, INCLUDING CONSIDERATIONS OF ENVIRONMENTAL AND FINANCIAL RISK.
- HOW WILL RISK BE MANAGED?
- WHAT SPS COSTS ARE ESTABLISHED, AND WHAT IS THE RANGE OF UNCERTAINTY?
- WHAT IS NECESSARY IN THE WAY OF A DEMONSTRATION OR PILOT PLANT IN ORDER TO COMMERCIALIZE SPS?

INDICATIONS FROM DEVELOPMENT QUESTIONS

Review of the development questions enumerated to this point provides the indications tabulated on the facing page.

Indications from Development Questions

- PROTOTYPE SUBSYSTEMS AND PRODUCTION PROCESS PILOT PLANTS NEEDED TO ESTABLISH CONFIDENCE IN HARDWARE COST AND PERFORMANCE
- A BROAD SPECTRUM OF SPACE OPERATIONS EXPERIENCE IS NEEDED. NOT NECESSARY TO "BUILD AN SPS" BUT MUST OBTAIN EXPERIENCE IN ALL CRITICAL OPERATIONAL SITUATIONS, SUCH AS:
  - SUBSYSTEM OPERATIONS
  - CREW TASK DESIGN AND PRODUCTIVITY
  - ENVIRONMENTS
- PRODUCT IS TECHNICAL AND COST CONFIDENCE; PRELIMINARY DESIGN AND SPECIFICATIONS FOR SPS DEMONSTRATION SYSTEM

DEMONSTRATION ISSUES

The present SPS program concept presumes that the development phase of SPS would be followed by a demonstration phase with the objective of demonstrating operational suitability of SPS for commercial use. Demonstration concepts for SPS have been studied over the past several years. A number of flight vehicle configurations have been developed. The facing tabulation ynopsizes some of the principal issues that have surfaced and provides a present judgment as to the objectives of a demonstration system.

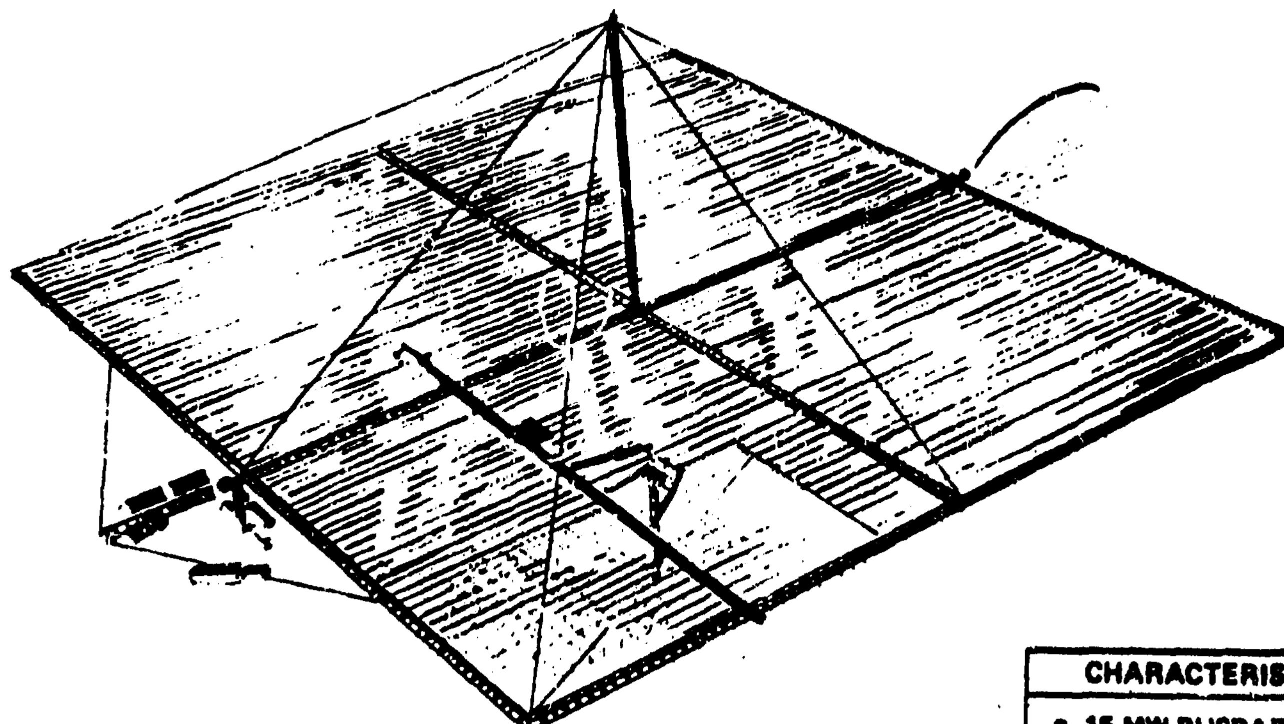
Demonstration Issues

- PREVIOUS STUDIES HAVE POSTULATED DEMONSTRATION SPS'S FROM 15 TO 10,000 MEGAWATTS
- THE REQUIREMENTS ON THE DEMONSTRATION SYSTEM HAVE NEVER BEEN CLEAR
- SUCCESSFUL COMPLETION OF THE RESEARCH AND DEVELOPMENT PHASES OF SPS SHOULD PROVIDE UNPRECEDENTED TECHNICAL AND COST CONFIDENCE
- IF A UTILITY COMPANY ACQUIRES AN EXPENSIVE POWERPLANT THAT FAILS AND CANNOT BE READILY RESTORED TO SERVICE, THE FINANCIAL CONSEQUENCES ARE SEVERE.
- THE DEMONSTRATION SYSTEM SHOULD THEREFORE DEMONSTRATE OPERATIONAL SUITABILITY OF SPS: GRID COMPATIBILITY, AVAILABILITY, AND REPAIRABILITY. ENHANCEMENT OF COST AND TECHNICAL CONFIDENCE WILL ALSO RESULT.

PHOTOVALTAIC SPS PILOT PLANT AND CONSTRUCTION CONCEPT

The accompanying illustration shows an early concept for a solar power satellite pilot plant developed by the Johnson Space Center in about 1975. This pilot plant was to be constructed and operated in low earth orbit. Subsequent studies considered the possibility of its delivery to geosynchronous orbit. In low earth orbit, the time over a given ground receiving station was no more than a few minutes per day. In geosynchronous orbit, the transmitter aperture was too small to provide beam intensities on the ground that could be utilized by a receiving antenna for electric power generation. This pilot plant concept, however, would have demonstrated construction and operation of large solar arrays and transmitters in space.

Photovoltaic SPS Pilot Plant And Construction Concept



CHARACTERISTICS
• 15 MW BUSBAR
• 340 X 10^3 KG
• 373 M X 373 M
• 100 M ANT.

COMMERCIAL DEMONSTRATOR

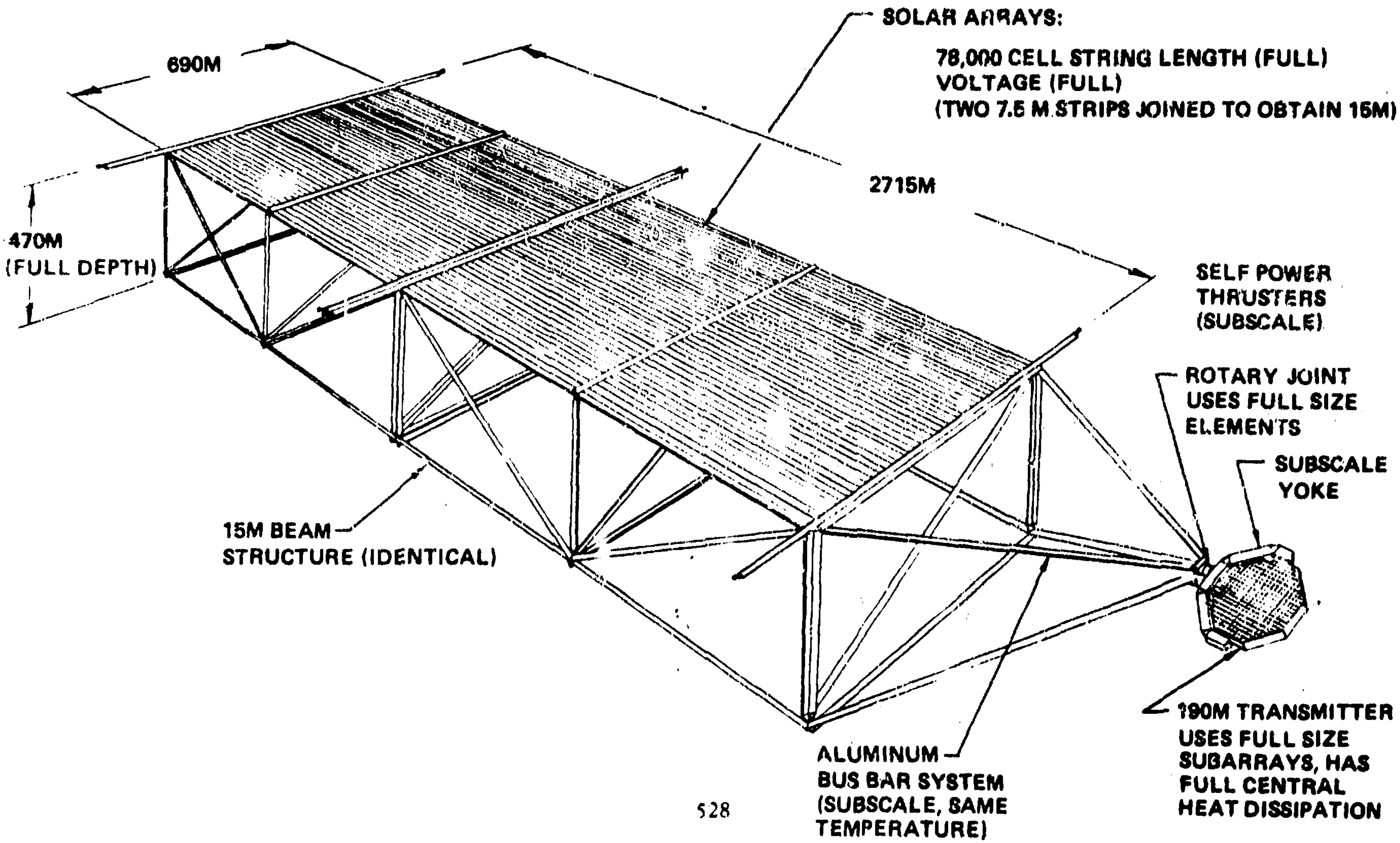
The accompanying illustration shows another SPS demonstration concept, this one developed by Boeing in 1978. It was, at that time, conceived as roughly the minimum-size system that could fully qualify all SPS components and subsystems for operation and serviceability in the SPS environment. Its transmitter aperture and power level, however, were also too small to provide meaningful power levels at the ground. It could provide all objectives of a commercial demonstration program excepting the demonstration of operability of an SPS with a power grid.

SPS

Commercial Demonstrator

BOEING

SPS-1812



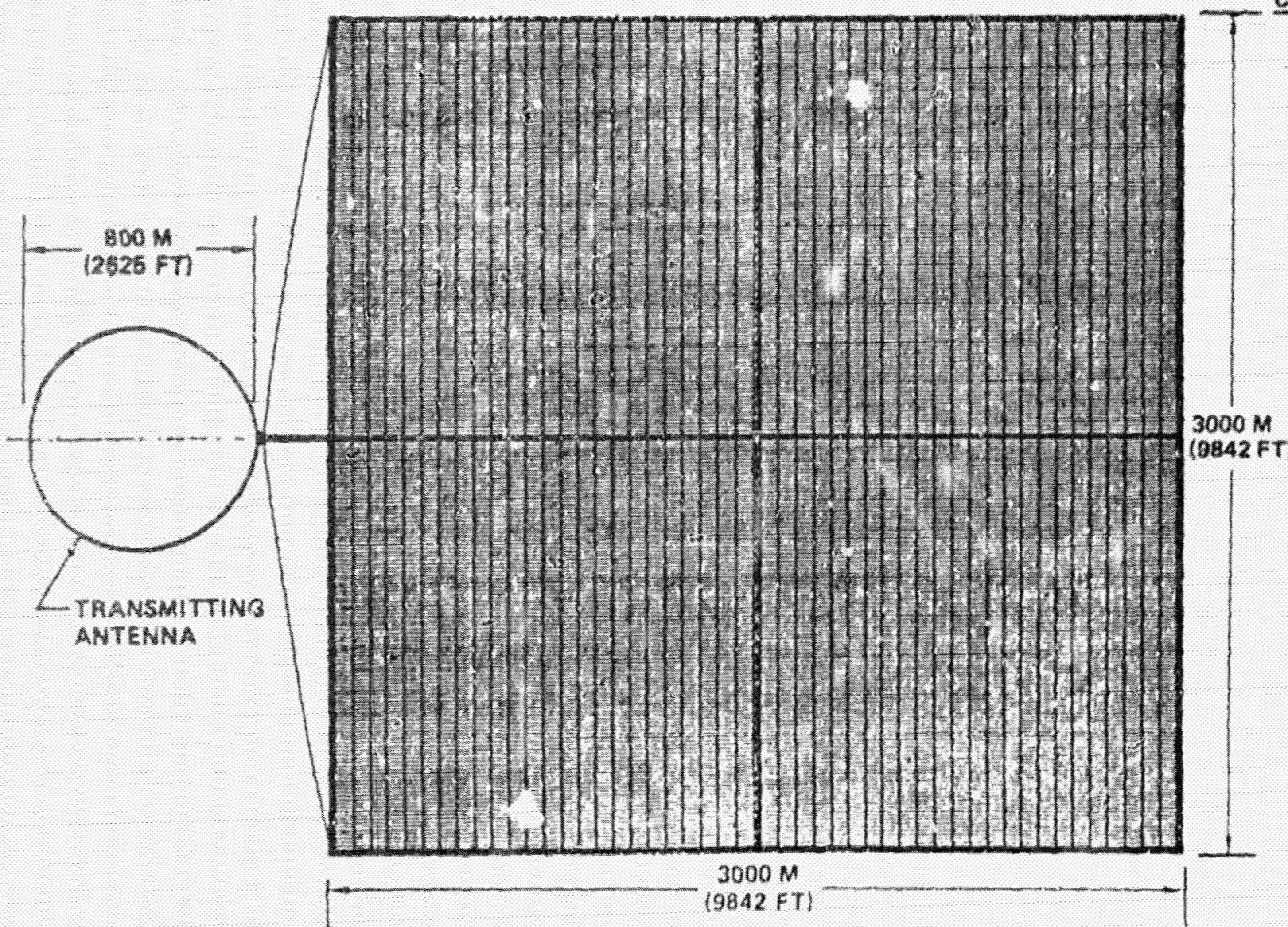
SPS ENGINEERING PROTOTYPE PHOTOVOLTAIC CONFIGURATION

Illustrated here is a still larger prototype SPS. This one was characterized by Boeing in 1976. It was capable of delivering about 500 megawatts to a receiving station on the ground.

SPS Engineering Prototype Photovoltaic Configuration

BOEING

SPS-2971



CHARACTERISTICS

- 1.2 GW_e (GEN)
- GEN MASS:
  5.2 M KG
  (11.5 M LBS)
- ANT. MASS:
  3.6 M KG
  (7.9 M LBS)
- AREA:
  502,000 SQ M
  (5,400,000 SQ FT)
- CONCENTRATION RATIO
  2:1

PAST AND FUTURE ELECTRIC POWER ALTERNATIVES USE PILOT PLANTS

The history of development of new electrical generation technology shows a consistent pattern of graduating from test facilities to pilot plants to commercial demonstrators. Several examples are tabulated on the facing page.

Past and Future Electric Power Alternatives Use "Pilot" Plants

(1976 DATA)

PAST:	PROGRESSION TO THE COMMERCIAL LIGHT WATER REACTOR	
	• EXPERIMENTAL REACTORS,	
	• DEMO REACTOR,	SHIPPINGPORT, PA
	• PROTOTYPE PLANT,	OYSTER CREEK, NJ
FUTURE:	GROUND SOLAR POWER (TOWER TOP TYPE)	
	• TEST FACILITY	(5 MW_t) ALBUQUERQUE, NM
	• PILOT PLANT	(10 MW_e) BARSTOW, CA
	• COMMERCIAL DEMONSTRATOR	(100 MW_e)
	BREEDER REACTOR (LIQUID METAL FAST BREEDER)	
	• FAST FLUX TEST FACILITY	400 MW_t
	• CLINCH RIVER BREEDER	380 MW_e
	• PROTOTYPE COMMERCIAL BREEDER	1,200 MW_e
	FUSION (MAGNETIC)	
	• EXPERIMENTAL POWER REACTOR 1 (20-50 MW_e)	
	• EXPERIMENTAL POWER REACTOR 2 ($>$ 100 MW_e)	
	• DEMONSTRATION REACTOR ($>$ 500 MW_e)	

DEMONSTRATOR PROVISIONAL REQUIREMENTS

Based on the preceding considerations a set of provisional requirements for an SPS demonstrator have been developed. First, it must operate at geosynchronous orbit. This is important because the ionizing radiation and plasma environment in geosynchronous orbit is significantly different from that at low earth orbit. Also, a geosynchronous location is essential in order to provide continuous operation with a ground receiving station.

Secondly, meaningful power must be provided to a utility grid in order to demonstrate operational suitability for baseload service.

A conclusive demonstration of reliable control of the power beam and its sidelobes is important to a final demonstration of environmental acceptability as well as showing suitability for continuous service.

The SPS demonstrator should show the capability of an SPS to deliver a high plant factor in the range of 0.8 to 0.9 or better. Achievement of a high plant factor is critical to the economic acceptability of a high capital cost, low fuel cost, renewable energy system.

It is clear that reliable and repeatable startup and shutdown is important. In the process of demonstrating this and the other objectives, SPS hardware and operations can be qualified for commercial service.

Finally, in order to demonstrate the ability of an SPS to provide a high plant factor over a long period of time, maintainability and repairability of the SPS should be included in the demonstration program.

Demonstrator Provisional Requirements

- OPERATE AT GEO
- PROVIDE MEANINGFUL POWER TO A UTILITY GRID (TENS TO HUNDREDS OF MEGAWATTS)
- DEMONSTRATE RELIABLE CONTROL OF POWER BEAM AND ITS SIDELOBES
- DEMONSTRATE PLANT FACTOR CAPABILITY
- DEMONSTRATE RELIABLE, REPEATABLE STARTUP AND SHUTDOWN
- QUALIFY SPS HARDWARE AND OPERATIONS
- DEMONSTRATE MAINTAINABILITY AND REPAIRABILITY

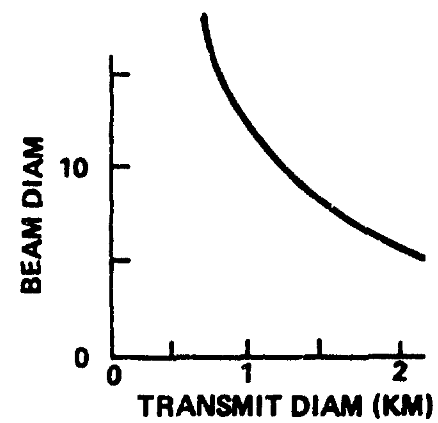
DEMONSTRATOR CONSIDERATIONS

The increasing definition of SPS hardware elements by the ongoing system definition studies has led to the considerations listed on the facing page. Of particular importance is the minimum power density achievable with the reference system design. It seems appropriate for a demonstrator system to consider a uniform antenna illumination since the relatively higher sidelobes of the uniform illumination will still be considerably less in intensity than the side lobes of the operating SPS. It is also clear that a large transmit aperture is needed in order to provide a beam diameter at the ground commensurate with a reasonable of rectenna size.

Demonstrator Considerations

SPS-2931

- LARGE ANTENNA APERTURES ARE REQUIRED TO ACHIEVE REASONABLE BEAM FOOTPRINT
- WITH REFERENCE SPS KLYSTRONS AND SUBARRAY SIZE 650 W/M^2 IS MINIMUM POWER DENSITY. (1 KLYSTRON PER SUBARRAY)
- SOLID-STATE OPTIONS LESS CLEAR, BUT COMPARABLE
- DESIRE ≈ 1 MW/CM^2 TO DRIVE RECTENNA
- LEADS TO 300-600 MEGAWATTS RF POWER AS MINIMUM; ROUGHLY SIZE OF REFERENCE EOTV



RECEIVED POWER 650 WATTS PER SQUARE METER - 800 METER APERTURE

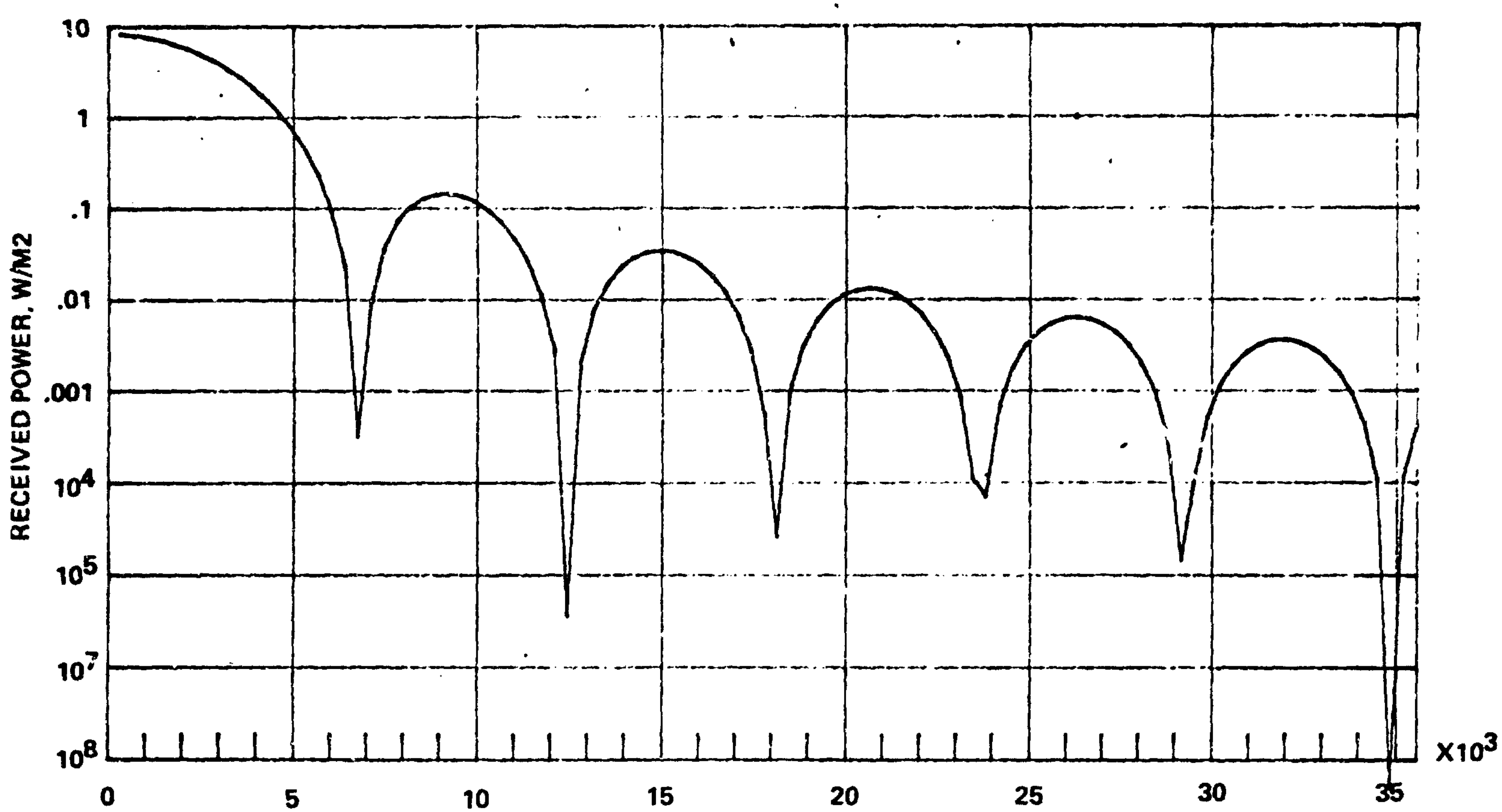
Patterns were computed for the minimum power constant illumination transmitter with an 800-meter aperture. The central beam strength is approximately 1 milliwatt per square centimeter, sufficient to drive a rectenna, albeit not at high efficiency. The first side lobe slightly exceeds 10 microwatts per square centimeter with the other side lobes at lower levels.

SPS

Received Power: 650 W/M2, 800-M Aperture (RF Power = 327 MW)

BOEING

SPS-2973

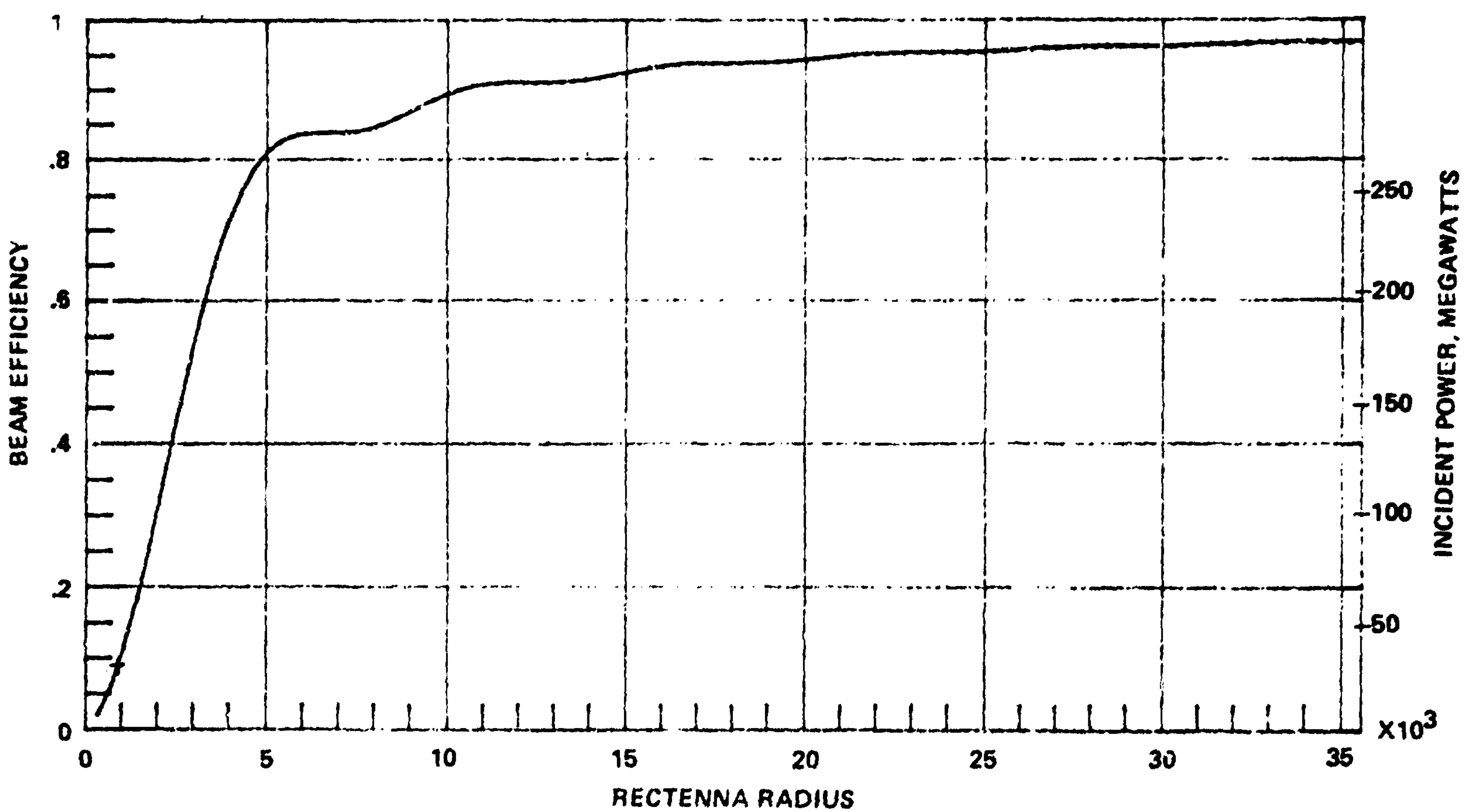


RECEIVED POWER 650 WATTS PER METER SQUARED - 800 METER APERTURE

Shown here is the beam efficiency as a function of rectenna radius. The right hand scale shows incident power on the rectenna as a function of radius. With an expected rectenna efficiency of roughly 75% to 80% at these power levels, 50 to 100 megawatts can be provided with a relatively small rectenna. This system, therefore, would meet the objectives of the demonstration of SPS in providing sufficient power to a utility grid to demonstrate operational suitability.

The solar array output power required to drive this system is in the range of expected power levels for the electric orbit transfer vehicles. Thus, it is conceivable that initial experimental EOTV's could be constructed at low earth orbit, used to transport SPS hardware to geosynchronous orbit, and then used to drive the demonstrator system. At the conclusion of the demonstration program, these EOTV's could then be refurbished and placed back into electric orbit transfer service.

Received Power: 650 W/M2, 800-M Aperture



SPS DEVELOPMENT ANALYSIS - WHERE WE STAND

Principal accomplishments of the development analysis are summarized on the facing page. The development program concentrates initially on issue resolution through research with a minimum expenditure commitment consistent with accomplishment of the objectives. The program then moves into an engineering development phase aimed at confidence building and risk identification. The final developmental phase of SPS demonstration concentrates on minimizing risks to utilities and managing the program financial risk to maximize the likelihood of success.

SPS Development Analysis – Where We Stand

SPS-2987

- PROGRAM PHILOSOPHY CLARIFIED
- RESEARCH PLANNING DATA BASE DEVELOPED
- QUESTIONS (OBJECTIVES) OF DEVELOPMENT BEING DEVELOPED
- APPROACH TO PROTOTYPING IDENTIFIED

ISSUE RESOLUTION – CONFIDENCE BUILDING AND RISK IDENTIFICATION – RISK MANAGEMENT